Advanced Robotics for Air Force Operations

Committee on Advanced Robotics
for Air Force Operations
Air Force Studies Board
Commission on Engineering
and Technical Systems
National Research Council

Robotics: Leverage for the Future

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Projected manpower shortages, shorter weapon response times, and the severe environmental conditions anticipated in combat make the use of robots more attractive in the U.S. armed forces. To help the Air Force assess the potential for operational use of robots, the committee (1) evaluated current and potential uses of advanced robotics to support Air Force systems, (2) recommended the most effective applications of advanced robotics, (3) identified high payoff areas for research and development, particularly at the component level; and (4) assessed the potential effects that robots will have on acquisition, logistics, and manpower considerations, such as education and training.

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STATEMENT OF TASK

While robots are gaining widespread use in industry, application of robotic technology has not progressed as quickly within the military. However, projected manpower shortages, shorter weapon response times, and the severe environmental conditions anticipated in combat make the use of robots more attractive. To help the Air Force assess the potential for operational use of robots, the committee will examine and recommend how to best direct research, development, and acquisition resources to make the most effective use of this technology. This study reviews the component technologies, infrastructure, data base systems, and management structure required to support the next generation of maintenance, repair, supply, and distribution systems in the field and at the depots as they pertain to robotics.

The committee will:

- evaluate current and potential uses of advanced robotic systems to support Air Force systems;
- recommend the most effective applications of advanced robotics;
- identify high payoff areas for research and development, particularly at the component level; and
- assess the potential effects robots will have on acquisitior, logistics, and manpower considerations, such as education and training.

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EXECUTIVE SUMMARY

Robotics *the augmentation or replacement of logistics and operational functions, normally performed by human beings, with semi-autonomous or autonomous systems that perform sensing, cognitive, and motor functions.*

Realizing that the Air Force faces pending manpower shortages caused by the declining pool of 18- to 24-year-olds, growing budget constraints, and the need to operate in increasingly hazardous environments, the Commander of the Air Force Systems Command asked the National Research Council, through its Air Force Studies Board, to help the Air Force assess potential uses of robotics technology in operations and support. The Committee on Advanced Robotics for Air Force Operations was established by the Air Force Studies Board in January 1987 to:

- evaluate current and potential uses of advanced robotic systems to support Air Force operations;
- recommend the most effective applications of advanced robotics;
- identify high payoff areas for research and development, particularly at the component level; and
- assess the potential effects robots will have on acquisition, logistics, and manpower considerations, such as education and training.

The committee limited the scope of the report to the potential uses of robotics to support combat and logistics operations. This examination included areas of preparation of aircraft for flight, missile maintenance and readiness, ground radar and communication systems, space activities, and the necessary maintenance, modifications, and logistics support in the field and at the Air Force Logistics Command (AFLC) depots. Remotely piloted vehicles, smart munitions, reconnaissance, and the pilot associate were omitted because they are being developed separately. The committee, at the request of the Air Force, limited its concerns about the need for robotics in manufacturing to remanufacturing at logistics depots. The impact of artificial intelligence (AI) on robotics was also excluded from the committee's study because other Air Force programs are addressing this area.

The committee attended presentations by the Air Force and other Department of Defense (DoD) agencies in Washington, D.C., and visited various Air Force bases where it heard briefings and saw Air Force units in operation. Finally, the committee reviewed documents describing various current and planned robotics programs of the Air Force, Army, Navy, DoD, NASA, Defense Advanced Research Projects Agency (DARPA), the Department of Energy (DOE), and industry.

CONCLUSIONS

After reviewing the Air Force programs in robotics, potential applications, and the state of the art in robotics technology, the committee concluded:

- The Air Force is not aggressively using or developing robotics technology.

- The Air Force has many opportunities to benefit from robotics.
- The Air Force has no organizational focus or champion for robotics.

RECOMMENDATIONS

General

The recommendations outlined in **Figure 1** are divided into three areas: organizational, technical, and philosophical-attitudinal. The organizational and technical areas must receive equal and sufficient attention. The effect of combining these two areas will greatly exceed the results obtainable from either factor alone. In addition, the committee believes that obtaining a "critical mass" of effort is necessary and will accelerate the subsequent return on investment. Isolated activity will have a negligible impact.

Implementation of these recommendations should help the Air Force to realize the full potential of the high technology that is available today, and on the horizon for tomorrow, to increase its efficiency, reduce risks, and increase overall effectiveness and readiness.

The committee does caution the Air Force that a well-defined strategy for implementation is needed to assure the successful application of the technology. Hasty introduction of systems that have not been fully developed and tested could be a major barrier to future acceptance of robotics. The committee does, however, believe that this initiative properly lies within the purview of the Air Force after their review of this report.

Technical Recommendations

The technical recommendations are divided into applications and research and development (R&D) (**Figure 1**). The applications are in turn subdivided into short- and long-term applications (**Figure 2**). The short-term applications are differentiated into those that are more effectively brought about through transfer from industry and those that are Air Force-specific and in need of internal development.

- **Applications**

Robots are well suited to Air Force operations that are routine, manpower-intensive, and hazardous. In war, these operations are even more hazardous and there are more of them. In peace, the application of robotics to routine operations would reduce manpower needs and personnel exposure to hazards, and would verify and validate these applications for wartime operations.

Within the scope of this study, perhaps the most fruitful area for the application of robotics is in the AFLC. There are many potential applications within air logistics center (ALC) repair facilities. Further, increased use of robotics by the AFLC and the ALCs will provide the Air Force a surge capability to meet wartime or contingency operations. Additional benefits would be gained through the verification and validation of robotics in potential combat applications.

The committee considered five major areas for application:

- •• where there is an increased danger to humans as in handling of hazardous materials, chemical/biological/-radioactive (CBR) environments, and combat conditions;
- •• in maintenance, food service, medical and clerical tasks, and wherever manpower has proved to be a major element (lack of trained personnel or where many people are needed);

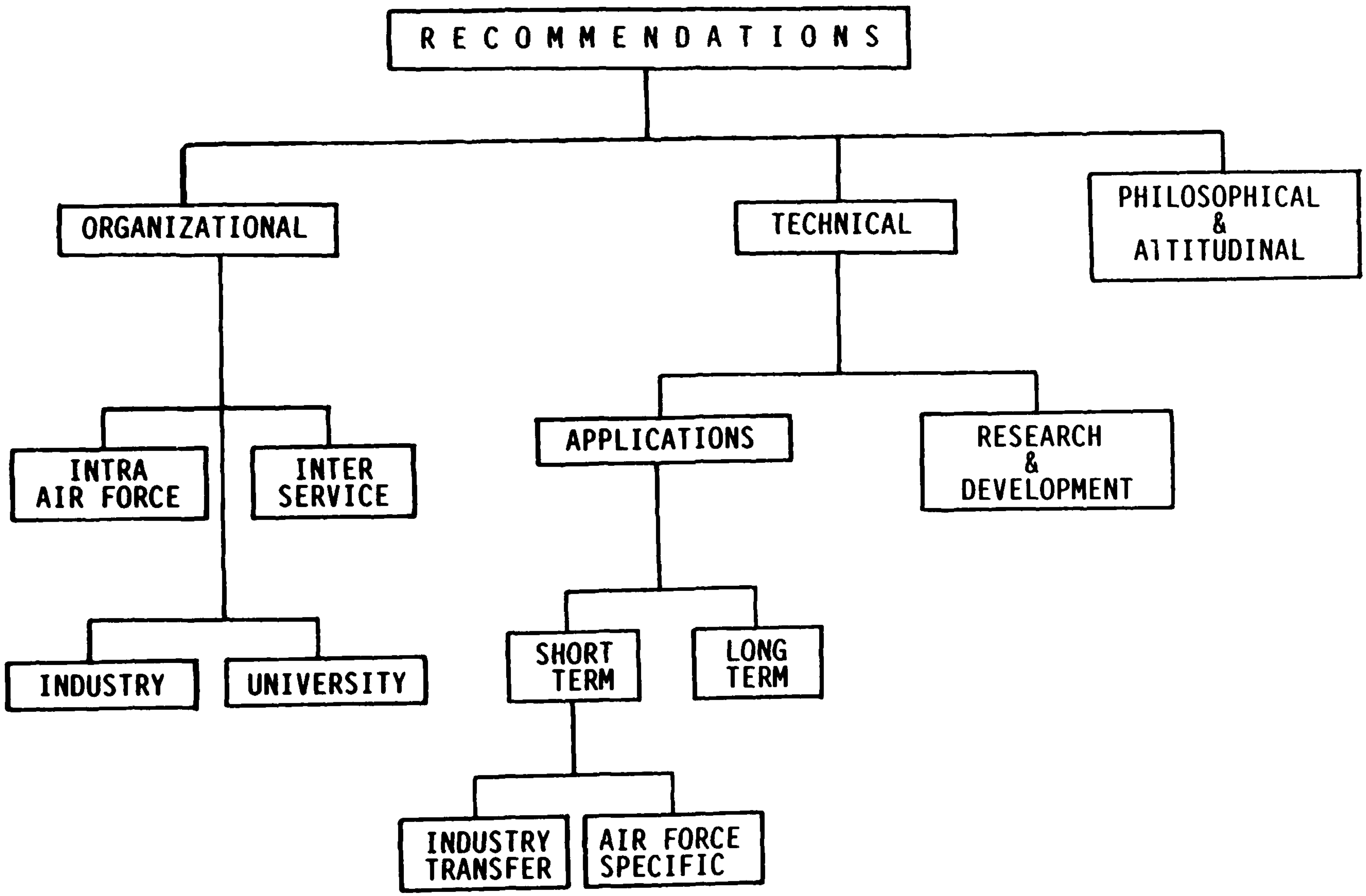

FIGURE 1 RECOMMENDATIONS

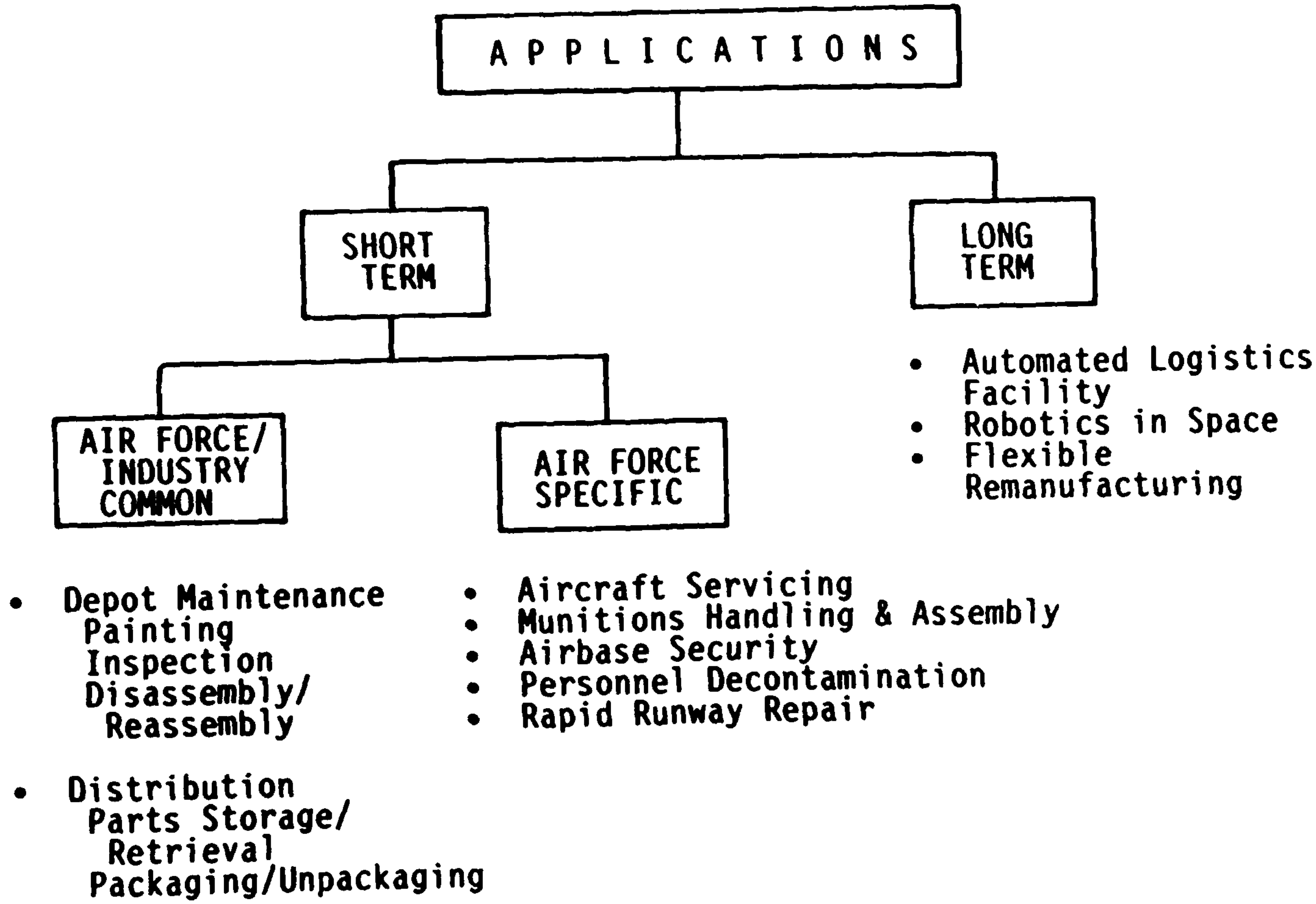

FIGURE 2 APPLICATIONS

- •• where cost containment is a major concern, as in manufacturing and maintenance;

- •• where the effectiveness of combat forces and their enhancement is important, as in air base and storage depot sentry duty, combat situations, and aircraft, satellite, and missile applications; and

- •• *in* space-based labor for operations, construction, maintenance, and repair of platforms, space stations, and satellites.

In addressing areas of application, the committee considered the probability of success from both a technological and mission perspective, and measured these against short- and long-term relevance to the Air Force.

Recommended applications (**Figure 2**) fit into three major categories: (1) short-term applications common to both the Air Force and industry, (2) short-term Air Force specific applications that require adaptation of current technologies and limited research to meet specific Air Force needs, and (3) long-term Air Force specific applications that require significant additional research in various technologies before they can be developed and fielded.

Short-Term, Industry-Transferrable Applications: The committee recommends depot maintenance and distribution. Specifically, the Air Force should enhance such tasks as painting, inspection, and disassembly and reassembly, parts storage and retrieval, and packaging and unpackaging by transferring technologies now used by industry.

Short-Term, Air Force-Specific Applications: The committee recommends three applications that are important both in peace and war: *aircraft servicing*, munitions handling and assembly, and air base security. Two others that are important primarily in war are personnel decontamination and rapid runway repair. **Long-Term:** The committee recommends three long-term applications:

- •• A completely automated logistics facility. It is strongly recommended that the Air Force consider a "total" rather than an incremental approach to automated logistics. This facility would permit design for automation and full integration of all service functions, including data bases and inventory.

- •• New emphasis on robotics in space.

- •• Flexible re-manufacturing.

- **Research and Development**

To support the above applications, the Air Force should place research and development emphasis on the following four major areas of technology:

•• **Computer Control Systems.** The Air Force should focus on formal models for hierarchical control, next generation intelligent software, and new architectures for control including: distributed, parallel, and supercomputers.

•• **Sensor Systems.** Improved individual transducer capabilities are needed as outlined in detail in the report, as well as advances in multi-source sensor fusion.

•• **Actuation Systems.** Research is required in the area of multi-criteria control of modular lightweight serial and parallel architectures, physical plant modeling in real time, and adaptive control for process disturbance rejection.

•• **Human Interface Systems.** The committee recommends research and development to balance human and computer *control*. In addition to strictly autonomous systems, the committee sees a significant continuing role for a man in

the loop in high-level supervisory roles *for remote robots.*

Organizational (Figure 3)

- **Air Force Robotic Focal Point**

The most important organizational issue for the Air Force with respect to robotics is to provide a focus, particularly as it affects applications in the logistics and operational areas. There is no focal point within AFSC or the various product divisions to which the operating commands can turn to fulfill their needs. There is no System Program Office (SPO), such as exists for engines, simulators, and electronic warfare, to champion and make possible the application of robotics.

While no substantive requirements "push" for robotics has come from the operating commands to date, part of this apathy is "cultural" since robots tend to be viewed in the context of manufacturing. Manpower shortages and hazardous operations may sharpen their interest, but current manpower appears sufficient and the nation is at peace.

The Air Force should identify a focal point or organization with requisite authority sufficient to pursue a more aggressive development of robotics. Toward this end, the Air Force should establish a Robotics and Automation Center in a selected division of the AFSC. This division would have responsibility for all robotics related R&D and automation applications for the Air Force.

- **Manpower - Training and Education**

The addition of robotic elements should help reduce manpower in certain areas. However, there will be a need for specialized training to program, operate, and maintain robots and the associated computers. The Air Force must place increased importance on training and education to accommodate its specialized needs and applications. The Air Force should also establish continuing education programs to support the increased requirements of these programs. The Air Force should strengthen its ties with universities, sponsor courses in robotics, and support continuing education programs.

Career opportunities must also be made more attractive and retention rates improved. The Air Force should establish an enhanced career path in the disciplines necessary to support automation and robotics programs.

- **Technology Lifetime Time Constant**

The Air Force should recognize the need to field systems that will have an adequate lifetime before obsolescence. This can be done only by reducing the current time to develop and field systems and subsystems.

- **Design for Robotics**

The Air Force should design new products and systems for robotics. Toward this end, it is appropriate and timely to incorporate requirements for robotics, as well as design for human factors in Requests for Proposals (RFPs).

- **Pilot Program**

The Air Force should establish a pilot program to demonstrate full integration of automation and robotics concepts from the conceptual design phase through production and testing. In this way, the use and effective realization of robotics will be seen in the shorter term and the automated logistics facility in the longer term.

- **Automated Logistics Facility**

Similarly, the Air Force should establish an advanced prototype logistics facility that incorporates automation and robotics specifically applied to logistics problems. It is anticipated that the

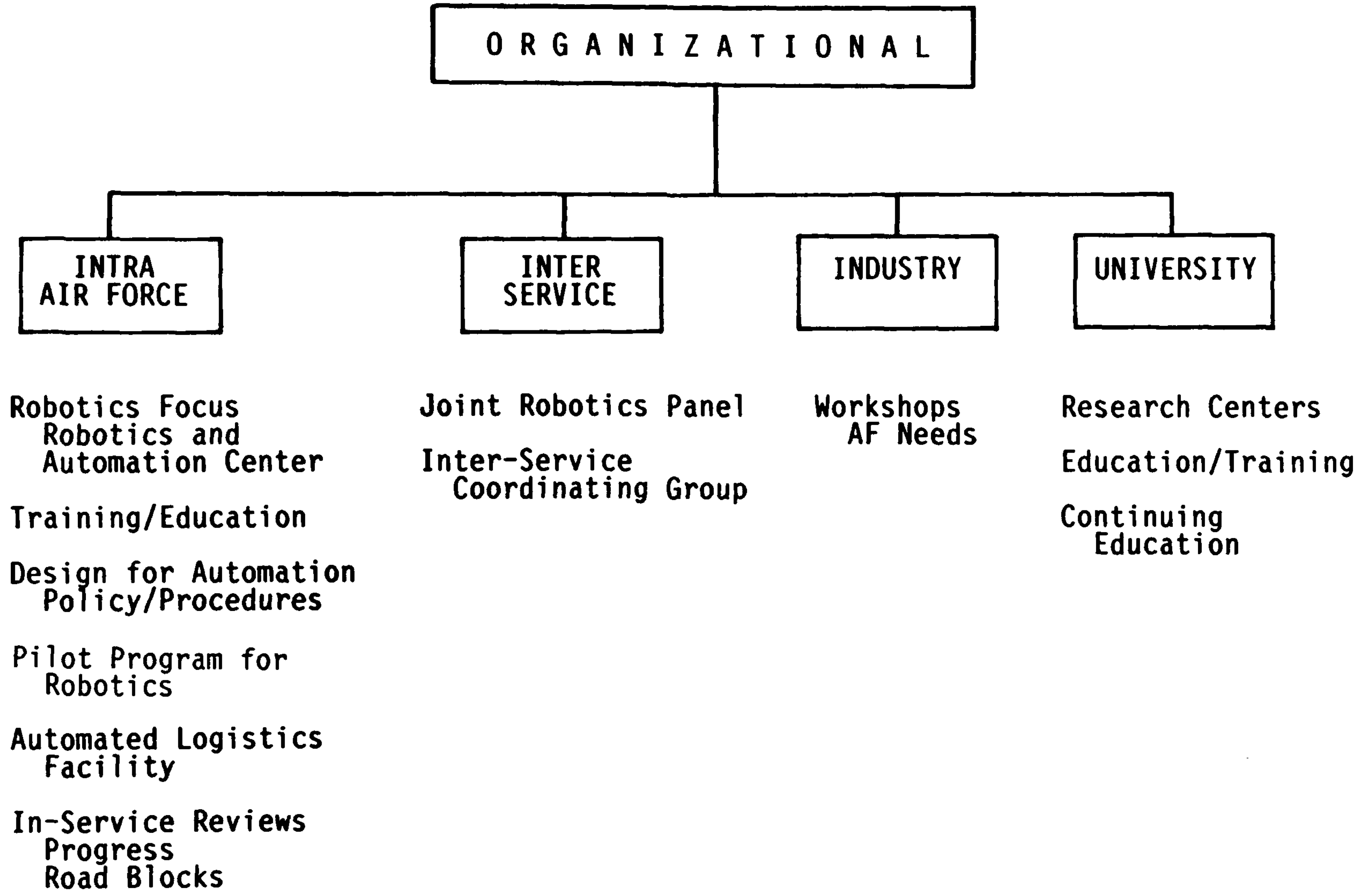

FIGURE 3 ORGANIZATIONAL

product as well as the process would be designed for automation.

- **Inter-Service and Intra-Service Coordination**

The committee recommends increased technology transfer both inter- and intra-service and with industry and academia to include shared R&D programs and training facilities. The DoD Joint Directors of Laboratories, Joint Technology Panel for Robotics, which was created to promote cooperation among the services, should be revitalized. Greater support needs to be provided to this panel because of its significance in bringing the services together to work toward a common goal.

The committee also recommends formation of an inter-service coordinating group to work with the private sector.

Also, the Air Force should conduct regularly scheduled workshops for industry to identify Air Force needs and requirements, primarily in the area of technology transfer.

- **Additional Recommendations**

The Air Force should conduct regular in-service reviews to determine the progress of its robotics program and to discuss problems that may arise.

Finally, the Air Force should conduct a short follow-up study three years from now to review the status and progress of its robotics program. This study would provide continuity of objective and help ensure the long-term focus for this area of technology.

1.0 INTRODUCTION

1.1 Background

The Committee on Advanced Robotics for Air Force Operations was established by the Air Force Studies Board (AFSB) in January 1987 at the request of the Commander, Air Force Systems Command. The committee was convened to help the Air Force assess the potential applications for robots in operational and support environments.

1.2 Scope

For this study, the committee defined robotics as: *the augmentation or replacement of logistics and operational functions, normally performed by human beings, with semi-autonomous or autonomous systems that perform sensing, cognitive, and motor functions.*

The committee was asked to evaluate current and potential uses and recommend the most effective applications of advanced robotics, identify high payoff areas for research and development, and assess the potential effects of robots on acquisition, logistics, manpower, education, and training. The committee sought to identify short term applications where the need is real, the approach straightforward, and the technology available. Genuine need was the main concern for the long term applications. At the request of the Air Force, the committee deemphasized assessment of the need for robotics in manufacturing because this area is being explored by other Air Force studies. Also, the impact of artificial intelligence (AI) on robotics applications was generally excluded from this study because the Air Force's collaborative AI research program with industry is addressing this area.

The scope of this report on Air Force activities differs from previous robotics reports conducted for other services in several ways. A report prepared for the U.S. Army, *Applications of Robotics and Artificial Intelligence to Reduce Risk and Improve Effectiveness* (National Academy Press, 1983), had no such limitation on the consideration of AI. Of greater importance, the Army study report looked at all the Army efforts in robotics and recommended several that would be suitable for development into demonstration projects within a two- to three-year period. The Air Force tasking in the present case involves looking at the longer term aspects of robotics R&D and applications to determine what should be done and where to place the emphasis.

The committee reviewed an earlier study for the Air Force by Honeywell, Inc. (*Robotics Application Study for Air Logistics Centers*, January 1987) because it was one of the few studies current in the area of this investigation and because it could be perceived to parallel this committee's study effort. The Honeywell report was supplementary to the committee's undertaking; it concentrated on specific applications for Air Force depots, but did not examine technology base concepts that cross-fertilize development of multiple applications, especially outside the depot environment.

1.3 Study Approach

The committee began this study with a series of presentations by the Air Force and other DoD personnel in Washington, D.C., followed by visits to var-

ious Air Force bases where it heard briefings and saw Air Force units in operation.

The committee recognizes that the few Air Force bases it visited are representative and not all inclusive. As such they gave us only a brief glimpse of Air Force operational and logistics requirements. The goal was to understand Air Force operational and logistics systems and to globally ascertain current Air Force uses of robotics. The committee also wanted to learn the weaknesses and needs within the present processes that appear to merit pursuing short term robotic applications and to identify long range potential for robotics efforts given the necessary incentive and R&D investment.

Since the committee did not hear about all the current robotic programs, it has focused on those areas where it received information and extrapolated, where possible, from its own technical background and experience.

Early in the study, it became clear that the committee needed to learn where robotics could enhance, not just replace, humans in the total system operation. Greater use of robots by the Air Force is viewed not as a way to replace people (except in hazardous environments) but as an augmenter of human capabilities and a force multiplier -- to add to productivity and free personnel for more demanding tasks for which people are best suited.

The primary intent was to determine where robotics could be used to meet Air Force requirements. From this initial determination and after a careful screening process, the committee was able to endorse a course of action for selected robotics applications and to recommend R&D efforts needed to produce a successful robotic program tailored to meet the Air Force's unique requirements.

2.0 POTENTIAL ROBOTIC APPLICATIONS IN THE AIR FORCE

2.1 Introduction

The applications discussed in this section are the result of information the committee received at briefings and visits to Air Force installations and from a review of related studies. The following systems have components of robotics, but are being developed separately and are omitted from this discussion.

- Smart Weapons
- Remote Piloted Vehicles (RPVs)
- Reconnaissance
- Pilot's Associate

The committee did not examine the application of robots in a direct combat role but instead looked at the potential uses of robots to support combat and logistics operations. This examination included preparation of aircraft for flight, missile maintenance and readiness, ground radar and communication systems, space activities, and the necessary maintenance modifications and logistics support in the field and at the Air Force Logistics Command (AFLC) depots.

In peace and in war, many routine Air Force operations are both manpower intensive and hazardous. Many of these operations are compounded during *wartime*, when increased productivity (e.g., sortie generation) is the norm and hazardous operations, aside from direct combat, are also increased. In peacetime, the application of robots to routine operations would have another major benefit besides reducing manpower needs and personnel exposure; these applications can be verified and validated against wartime operational requirements.

Perhaps one of the most fruitful areas for the application of robots lies within the Air Force logistics system. Increased use of robots by the Air Logistics Center's (ALC) repair facilities and lines will provide a surge capability for wartime operations.

Tables 2-A and 2-B list specific areas within the Air Force where we believe robots can be successfully applied in both the operational and logistics fields. In both the Primary Operations **(Table 2-A)** and Support Operations **(Table 2-B)** areas, an initial minimum capability may be commercially available or within the state of the art. For some applications, available technology could be adapted to the need and thus reduce costs. For other applications, additional R&D will be required to enhance the minimum capabilities that currently exist or to achieve the desired functional capability. However, since some of these technologies have potential commercial application, added benefits and economies may be achieved. The applications considered by the committee are now discussed in more detail.

2.2 Servicing Primary Operations

Aircraft

Aircraft Deicing. Aircraft parked on the field in snow and sleet must be deiced before takeoff. At operational bases, deicing units are operated by a driver and a hose operator. The latter stands on a "cherry picker," exposed to the elements, and sprays solution over the aircraft wings and tail, paying particular attention to the control surfaces. The operator's job is difficult, uncomfortable,

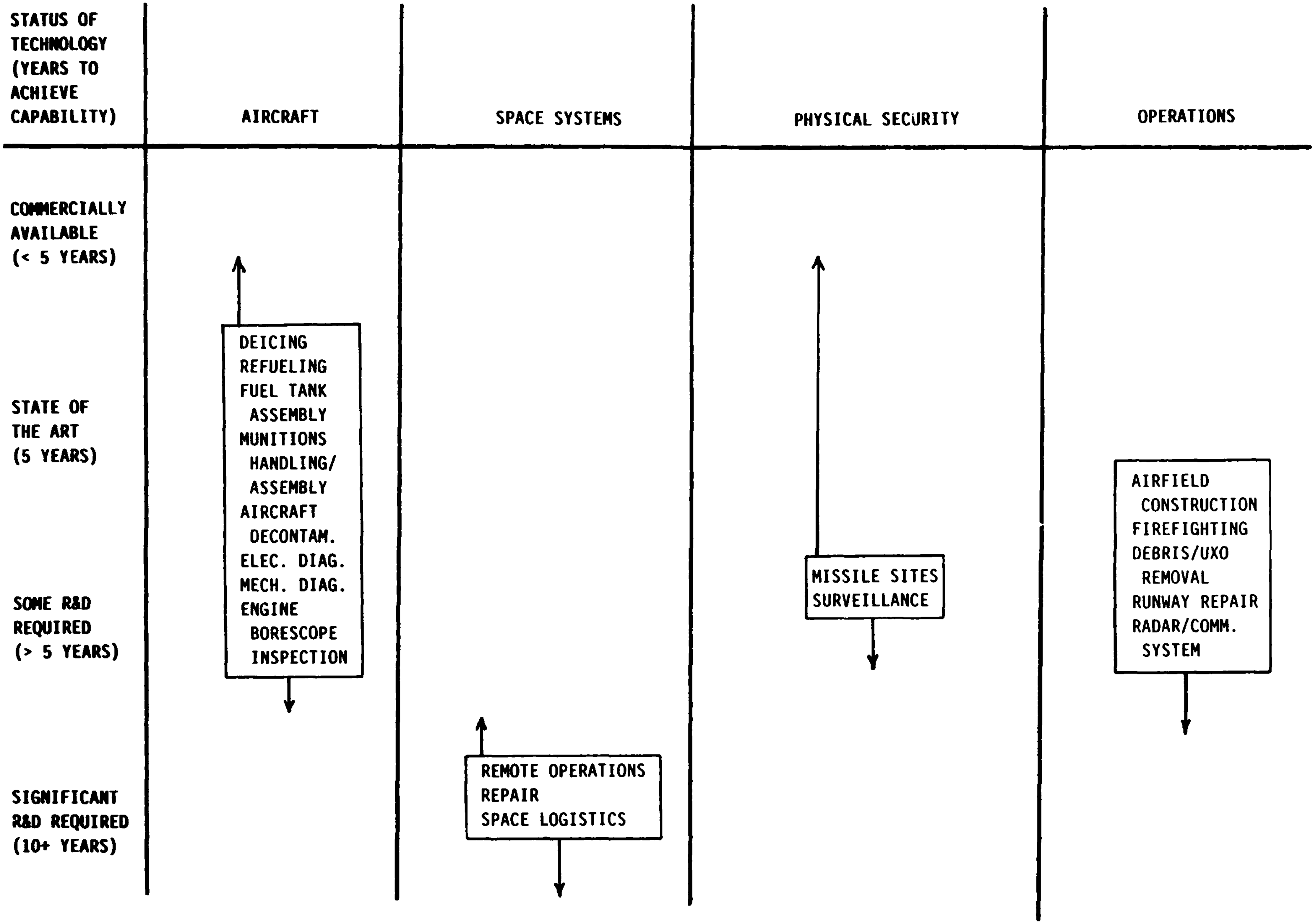

TABLE 2-A

POTENTIAL AREAS FOR THE APPLICATION OF ADVANCED ROBOTICS

PRIMARY OPERATIONS

STATUS OF TECHNOLOGY (YEARS TO ACHIEVE CAPABILITY)	HEALTH SERVICES	FOOD PREPARATION	FACILITY CLEANING	MAINTENANCE, REMANUFACTURING, AND MODIFICATION	MATERIAL HANDLING
COMMERCIALLY AVAILABLE (< 5 YEARS)	JANITORIAL SERVICES PATIENT ASSISTANCE FETCH & CARRY	FOOD PREPARATION COOKING & DELIVERY JANITORIAL SERVICES	JANITORIAL SERVICES	AIRCRAFT AND COMPONENT PAINTING AIRCRAFT AND WEAPON CORROSION TREATMENT JIGS/FIXTURES ELIMINATION FABRICATION RIVET/DERIVETING WELDING CUTTING COMPOSITE REPAIR PRECISION NDI ASSEMBLY/DISASSEMBLY	SUPPLY PACKAGING TRANSPORTATION
STATE OF THE ART (5 YEARS)					
SOME R&D REQUIRED (> 5 YEARS)					
SIGNIFICANT R&D REQUIRED (10+ YEARS)					

TABLE 2-B

POTENTIAL AREAS FOR THE APPLICATION OF ADVANCED ROBOTICS

SUPPORT OPERATIONS

and frequently hazardous as a result of slippery footing, cold, spray, and high winds. Heat may also be applied by the ground crews to the windshield and windscreens to remove snow and ice.

An alternate solution to accomplish the process is to control the hose from a cab in a teleoperator mode. A robot spray arm with TV vision cameras would remove the operator from the "cherry picker" and a hazardous environment while increasing efficiency through a decrease in the application time required for the process. A long-term solution would be to have the driver in control. The driver would position the vehicle in various predetermined positions to an aircraft and then the hose manipulator would use preprogrammed patterns to carry out deicing functions. The driver would monitor progress with feedback from manipulator-mounted cameras and repeat subroutines or go into teleoperation mode as appropriate. The same deicing vehicle would accommodate a hot-air nozzle when deicing the nose radar dome and canopy surfaces.

Aircraft Ground Refueling. Aircraft refueling operations are highly repetitive, moderately manpower intensive, and are moderately hazardous. The current operation requires a fuel truck, various large hoses on the ground, and a crew of two or three. These include personnel at the refueling nozzle, fire extinguisher, the major hose junction, the truck, and a supervisor. All would currently be exposed in a chemical, biological, or radioactive (CBR) warfare environment.

Robot application would reduce the size of the crew, remove them from any hazardous environment, and speed up the refueling process by adding a robot arm to the refueling truck, have the truck driver operate the boom, and use the air-to-air refueling port on the aircraft. The boom would not only transfer fuel, but would be equipped with a fire extinguisher element that would be instantly available. The truck would be sealed against any CBR intrusion thereby protecting everyone from the hazardous environment.

The reduction of personnel would more than offset the cost to modify the trucks. The number of refuelings per day makes this a good investment. Faster refueling would add to the sortie capacity during wartime, and the elimination of personnel from any CBR environment would give an enhanced wartime capability (**See Figure 2-1**).

Fuel Tank Assembly. A sporadically labor-intensive activity that accounts for a significant percentage of squadron support personnel (total population of a squadron is approximately 650 people) is fuel tank assembly. This task must be done in the field, so all automation must be portable, easily set up, highly reliable, and user friendly. It may not eliminate all manpower requirements, however.

External aircraft fuel drop tanks are stored and transported, disassembled and nested for rapid transportability in large numbers because they are highly expendable in wartime operations. At deployed locations, tanks are assembled with nuts, bolts, and rivets. The assembly is time-consuming and repetitive. An F-16 study determined that two workers took an average of 10.5 hours to assemble one tank. The tanks sometimes leak after assembly, and disassembly, inspection, reassembly and further testing is required. This process requires two man-days for each aircraft sortie. A squadron of 24 aircraft flying 50 sorties a day would require 100 man-days to do nothing but assemble drop tanks. Redesign of drop tanks to use robotic assembly would save most of this manpower. Such a robot system would be considerably more mobile and effi-

cient than having to supply 100 workers and move them to remote operating sites along with their associated support personnel and supplies.

The requirement for portability and advanced base utility place the above assembly task in the "operational use" robotic category rather than the more classical in-plant manufacturing. Such assemblies must be lightweight and portable to facilitate transportation for deployment. In wartime, robotic fuel tank assembly would contribute significantly to manpower savings and increased sortie generation.

Munitions Handling and Assembly. For reasons of safety, storage, and transportation, weapons must be built up as sorties are generated. There is a significant difference in workload by available manpower in the peace versus war scenario. In wartime operations, manpower (15 to 25 men) is drawn from other activities to augment the weapon build-up process. The build-up is repetitive and requires hand tools. A single aircraft uses a relatively small number of different weapons. However, operations by a squadron of tactical aircraft (F-16s for example) would require considerable manpower augmentation. The repetitiveness of the task combined with the potential requirement for increased manpower resources in war make this an attractive potential application for some form of automation or robotics. Because the weapon assembly line handles a variety of weapons, there may be common components and parts that lend themselves to automation. The drawings given to the committee were simplified, but there appears to be a potential for portable automation cells that could be set up in the field. The potential for this application is worthy of further detailed study.

Munitions Loading. Munitions loading is another repetitive activity that requires increased manpower in wartime conditions. For the heavier weapon loads normally associated with bomber aircraft, redesigned loading processes and equipment would speed the process, save manpower, and allow loading in a broader range of operational and climatic conditions. For tactical aircraft, robotic weapons loaders would reduce the number of personnel required and lessen their exposure in a hazardous environment. Currently, the aircraft loading and arming process does not have the design features necessary to accommodate robotic loading. **(See Figure 2-2.)**

Aircraft Decontamination. Aircraft contaminated during chemical or biological attack must be decontaminated before maintenance or flight preparation. Today aircraft are cleaned by trained decontamination personnel wearing chemical and biological protective clothing; they can work only as long as they are able to bear the temperature and humidity in their sealed suits. The time and effort required to dress in multiple layers of protective clothing, exit safe shelters, decontaminate the planes, return to decontaminate their exterior clothing, and then reenter safe areas greatly reduces personnel efficiency. The physical constraints of the protective clothing reduce vision, hearing, and mobility, which further reduce performance efficiency. Robot decontamination of aircraft exteriors would greatly reduce the need for personnel in this environment, reduce the hazards to which they would be exposed, and free personnel for other necessary wartime activities. A "car wash" concept would be feasible, but probably would be applicable to overseas use only in selected areas. A vehicle with functions common to the deicing requirement should be possible.

FIGURE 2-1 AIRCRAFT REFUELING ROBOT (MODEL). Robot has inserted the nozzle in the refueling receptacle on F-16 aircraft. Lt Sam Hagins is holding the teach pendant of the robot. [Courtesy Dr. Mangal Chawla, AF Wright Aeronautical Laboratories/FIEMB, Wright-Patterson AFB, Ohio.]

FIGURE 2-2 MUNITIONS LOADING ROBOT (MODEL). Capt Davis is observing the re-arming exercise (missile loading) by the robot on the wing tips of F-16 aircraft. [Courtesy Dr. Mangal Chawla, AF Wright Aeronautical Laboratories/FIEMB, Wright-Patterson AFB, Ohio.]

Aircraft Electronic Diagnostics. Correct diagnosis of aircraft electronic system malfunctions remains a major problem for the Air Force. Often, the reported problem from the aircrew cannot be determined on the ground. When a component is removed and tested at an intermediate repair facility on the base, it may be found to be in perfect operating order. Similarly, a component that is shipped to a depot for testing and repair may be found to be in satisfactory operating condition by the depot. Some major electronic components have had up to 75% of reported problems result in no actual repair. Robotic aids to improve diagnosis would help reduce the inordinate workload which false alarms (or maintenance misdiagnosis) produce. **Figure 2-3** shows typical electronic problems in F-15C fire control system maintenance wherein over [illegible]0% of the time the problem cannot be replicated or the item retests satisfactorily. **Table 2-C** shows the current data on electronic diagnostics on two of our first-line fighters. The data show that significant improvements are needed.

Robot analysis tools should be able to improve proper diagnosis through better quality of measurement and analysis. Technicians will miss fewer faulty items or systems during maintenance trouble shooting and fewer false alarms will be generated. The result will be a safer and more mission capable system with reduced maintenance and downtime, and lead to fewer component removals and reduce follow-on testing, maintenance, packaging, and shipment of components to repair centers. More systems will be capable of meeting wartime performance requirements. This application will create a force multiplier effect, reducing the cost of maintenance in peace and reducing the false maintenance workload in war.

The National Security Industrial Association (NSIA), following a request from the DoD office for acquisition and logistics, has created a formal group to address integrated diagnostics. This effort includes industry, academia, and many branches of the government.

Aircraft Mechanical Diagnostics. Aircraft mechanical systems normally require less diagnostics than electronic systems, yet account for a substantial amount of aircraft maintenance and downtime. Mechanical systems frequently show wear and thus alter appearance or vibration patterns. Robot monitoring of mechanical systems would determine in-progress problems and allow corrective actions at opportune times, without requiring the aircraft to be removed from service for extended, unplanned periods. **Figure 2-4** shows that for the F-16A, mechanical diagnostics requirements exceed those of avionics systems.

Mechanical systems will become more important in aircraft maintenance as future electronic systems become more fault tolerant. Improved diagnosis through robotic measurement will help mechanical systems even more than electronic systems. The system downtime to remove and replace mechanical systems is longer than the time to remove and replace electronic components, consequently, the need for robotic quality measurement of mechanical systems is highly significant. Improved quality measurement should allow for the determination of component degradation over time, and thus permit a determination of which systems are best capable of being deployed for a given operational situation. Peacetime economy and wartime capability should both be significantly enhanced. The NSIA, in addition to the integrated diagnostics committee, has created a group, the Subcommittee for Mechanical Systems Condition Monitoring (MSCM), to investigate mechanical systems diagnostics.

Engine Borescope Inspection. The complete borescope operation of aircraft engines is tedious; it is difficult to visually assess the health of the engine parts under scrutiny. This problem is particularly frustrating because two-thirds of the commercial borescopes used are down for maintenance and repair at any given time. A typical engine's compressor and turbine stages are inspected every 55 hours. To control the borescope's path using robot technology would be a practical engineering task. The fiber-optic borescope would need to be made more reliable which would be a normal benefit of automating the physical task. One envisions logging the scene captured upon insertion and retraction of the borescope along known paths and correlating this view with video images that would be examined in real time or later at an inspector's convenience. Robot positioning of the borescope would maintain the same viewing location of the borescope. By using the visual reference of the last inspection, a comparison would be possible of the damage accumulation that has occurred in the interval. Manhours and engine downtime would be saved. Further, the health of the operating engines would be improved by gathering information that would show engine conditions requiring removal for preventive maintenance.

Space Systems

The Strategic Defense Initiative Organization (SDIO) briefed the committee on their development of a plan for robotics. The Air Force will be the developing agency for all SDI space-based assets, including space-based interceptor satellites, which will operate in high inclination, medium to high altitude orbits. These assets include the Space-Based Support Platform (SBSP), space-based fuel tankers, and Space Transfer Vehicle (STV). The Orbital Maneuvering Vehicle (OMV) is a planned NASA program with application to SDI and other satellite servicing. For a limited array of satellites with long lifetimes, it is cheaper to launch a replacement than repair a failed unit. However, for a large constellation of satellites, such as is planned by SDI, repair will become preferable to replacement to keep the total system functioning. The hazardous environment of space combined with the extreme cost to transport and re-supply personnel to operate in space safely, refuel and repair SBI and associated satellites, make this operational area an ideal candidate for robotics consideration. We believe the Air Force has a significant opportunity to apply robot technology in developing the necessary support assets for SDI operations.

Because SDI intends to service satellites on orbit, it is believed that robots possessing substantial autonomous capability would be required. Additionally, this servicing will require a space-based infrastructure of Orbital Replacement Units (ORUs), refueling units, OMVs, and other robot devices. Once the supporting SDI infrastructure is in place, on orbit support for both SBI satellites and the Space Surveillance and Tracking System (SSTS) satellites will be possible.

Robots designed for space assembly, repair, and resupply operations will require the best multi-function capabilities that robot technology can provide. These robots will have to be light, dexterous, and modular to do self-repair. Development of a space robot capability will require extensive R&D, but this area has a high potential payoff compared to the hazards of having people do the same work and the associated high cost of providing a safe environment.

The Air Force would benefit by monitoring or participating in the NASA Flight Telerobotic Servicer (FTS) program. But the Air Force should not

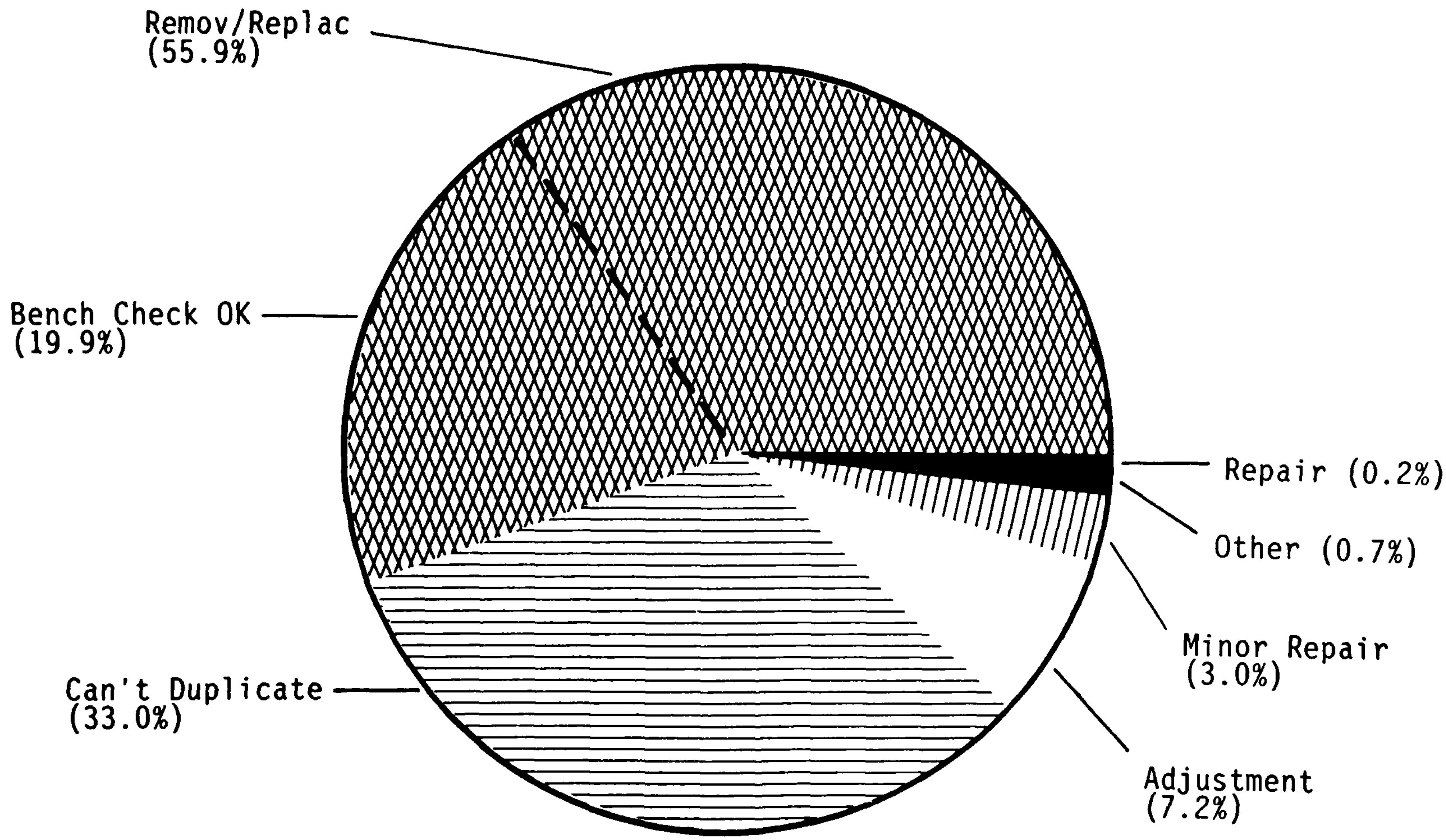

FIGURE 2-3

F-15C FIRE CONTROL MAINTENANCE

	F-15C	F-16A
Percent of Manhours Spent on Non-Malfunctions	42.5	46.2
Percent of Removals that Bench Check OK	26	28

TABLE 2-C

DIAGNOSTICS PROBLEMS

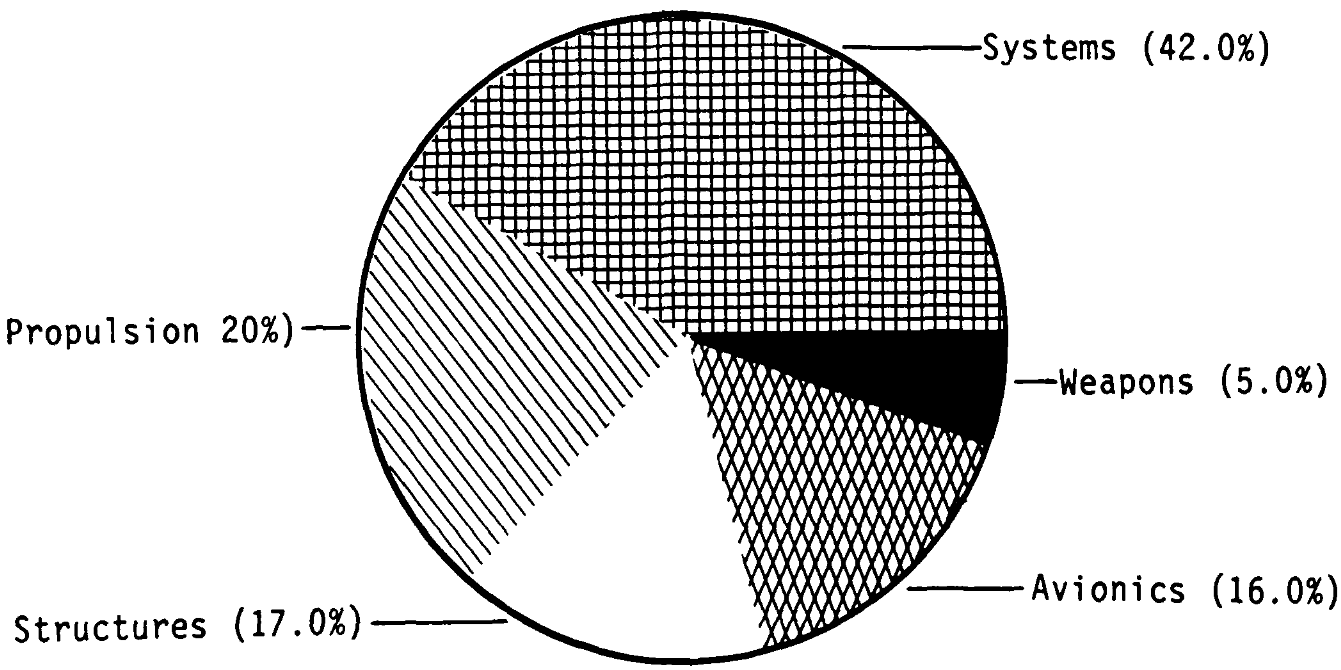

FIGURE 2-4

DISTRIBUTION OF MAINTENANCE MANHOURS ON F-16A EQUIPMENT

depend solely on NASA to supply all the technology that will be needed to support space operations into the next century. NASA is expected to continue to emphasize man-in-the-loop systems based upon its space station operations. NASA proposes to provide satellite servicing and repair by bringing satellites down from higher orbit and servicing them at or in the station that would be operating in low altitude, low inclination orbits.

The Air Force will need multiple autonomous robot systems capable of *in situ* satellite maintenance, particularly in high (including synchronous) and polar orbits, using ground-based supervisory control. An Air Force FTS would be preprogrammed on earth for most expected task scenarios. Earth-based astronauts would provide supervision, monitor the operation, select alternate programs, and, in unforeseen situations, block further action until simulations on earth created appropriate robot programs. In those unplanned, or unstructured task scenarios (i.e., 40 percent of the downtime for nuclear reactors is an example), human intervention through telepresence would be essential and would be done by direct astronaut use of "joystick" control to modify and augment an existing task scenario (from a menu) or to carry out full task control over the operation.

Normal situations and equipment for use in space are well defined. The expected operations are more structured than typical industrial robotic activities. They are, however, not highly repetitive as in manufacturing. In space, it is economical to do non-repetitive jobs automatically if they can be done without the physical presence of a human. "One-off" or non-recurring activities usually do not demand high speed. Cycle time is a meaningless term. A slow, methodical, and reliable execution is best.

The assembly and maintenance activities expected of a space robot would be done slowly with robot arms similar to human arms in extended reach. A space robot would contain a vast library of preprogrammed routines and subroutines. Because of short arm link lengths, simulations would be done in a one-G terrestrial environment and imitated by a robot on the space station. Program biasing for the projected effect of gravity can be accomplished in software given a complete description of the mechanics of the arms.

For robots to do space maintenance and servicing tasks, the supported product will need to be designed for robot assembly, disassembly, and repair. System interfaces and ORU grapple and fastening techniques will need to be standardized. But standardization alone will not be sufficient. Technology must be improved in order to deploy the desired robotic capabilities for SBI satellite support applications.

Physical Security

Air Force security is also manpower intensive: approximately 50,000 active duty, Air Force Reserve, and National Guard work in security. This is approximately eight percent of the total active and reserve forces. Also, several of the major commands contract out for additional security forces. Over the last 10 years, because of the increased threat of terrorism, the Air Force has increased its investment in security. The Air Force has emphasized the protection of nuclear weapons, equipment (aircraft and radar sites), and personnel. The basic idea of security operations is to deploy people and sensors and to raise physical barriers around assets to be protected. When a potential threat is detected, a response force is dispatched from security control.

A wide range of ground surveillance robots are available to counter a ground threat, including intrusion detection robots and intruder killers. These robots would be activated on command and placed as far away from the site to be protected as line-of-sight terrain features permit.

Robots have been proposed and developed for security services by several companies and government agencies. Two approaches have been proposed: robot systems as a mobile sensor platform and robot systems as active, potentially lethal defensive agents. There are valid concerns regarding whether a perimeter defense system should be lethal when triggered without human confirmation of the existence of a valid hostile intruder. Should such a system operate autonomously to provide adequate defensive capability? Whatever the operational configuration, mobility and navigation technology is being developed by several organizations. Robots have not reached a level of development to warrant active deployment, but such capability can be expected within the next several years.

Development activity on security robots has been carried out by the Department of Energy (DOE) at Sandia and Oak Ridge National Laboratory (ORNL) and in the Department of Defense (DoD) by the Defense Nuclear Agency (DNA), by DARPA, by the Naval Ocean Systems Center (NOSC), the Naval Surface Weapons Center (NSWC), by the Tank and Automative Command (TACOM) and Human Engineering Laboratory (HEL) in the Army, and by Electronic Systems Division (ESD) in the Air Force. Of these activities, the DNA activity and the DOE projects at Sandia (**see Figure 2-5**) and ORNL are particularly noteworthy. Both Sandia and ORNL have developed autonomous vehicles for security applications and have substantial funding. The DNA began a multi-agency project several years ago to develop a security robot. This project was originally intended to be the major DoD security robotic effort. Two phases of study have been completed. Phase three, development of a prototype, is on hold pending the test results of existing commercial products.

Larger companies have worked on autonomous land vehicles (ALVs) that could be used for security applications, notably the ALV projects at Martin Marietta, General Dynamics LSD, and Ford Motor Company; and the Army's Teleoperated Mobile Anti-armor Platform (TMAP) projects at Martin Marietta and Grumman. The TMAP is particularly interesting as a potential basis for a field security robot. This system can be used in either autonomous or remote control mode and will have substantial sensing, processing, and target tracking capability. Prototypes are under development. Finally, many university projects in mobile robots, particularly at Massachusetts Institute of Technology, Carnegie Mellon, Stanford, and Drexel Universities could have direct application to security systems.

Ballistic Missile Sites. Although the committee did not explicitly investigate ballistic missile systems, we believe that there are potential areas for the application of robotics and automation. Ballistic missiles systems (Minuteman II & III and the Peace Keeper System) enjoy a high degree of automatic monitoring and self-diagnostics. Literally hundreds of performance and functional parameters are monitored on a multi-second basis throughout the operating life of the missiles to ensure a high degree of reliability and accuracy. This class of systems clearly demonstrates that automatic diagnostics are available and in use today. The remoteness of these missile sites, and the absolute demands of security have imposed heavy manpower demands on the Strategic Air Command (SAC). The SAC Security

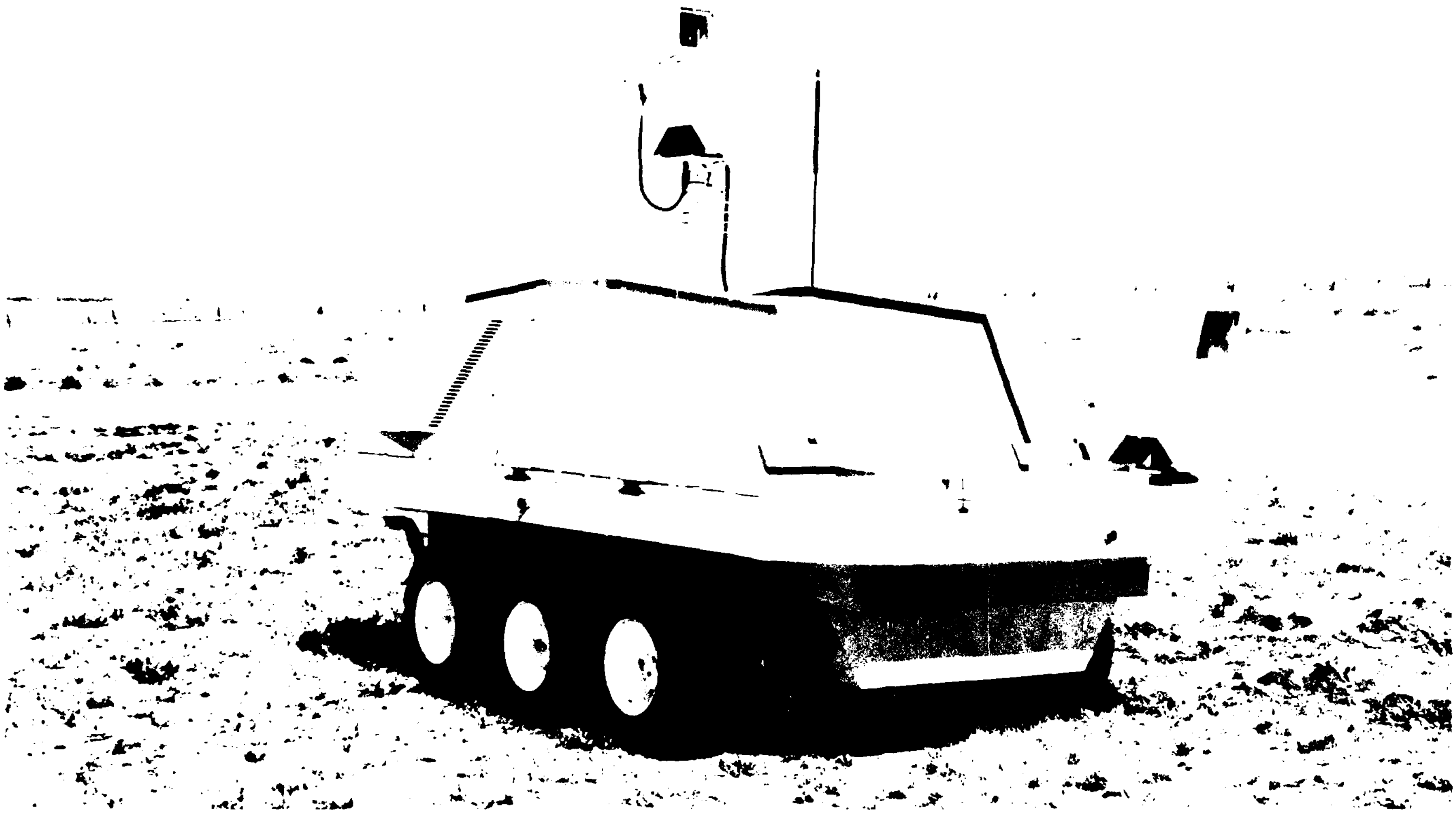

FIGURE 2-5 EXPERIMENTAL SENTRY ROBOT. [Courtesy James R. Kelsey, Advanced Technology Division 5267, Sandia National Laboratories, Albuquerque, New Mexico.]

Police force alone numbers over 17,000 personnel. The opportunity for reducing these manpower demands through the application of remote surveillance (security from afar) lends itself to the application of robotics.

Surveillance Following Attack. Knowledge of the extent of damage to an air base facility is necessary to determine what actions can and should be done and with what priority in order to return the base to operational status following an attack. The damage assessment needs visual information and a survey conducted of base needs in order to determine the hazards remaining. Both tasks can be combined and solved with mobile, sensor-equipped robot systems that can be deployed without danger to personnel.

Airfield damage assessment, mine and unexploded ordnance (UXO) location and identification might use smart walking or pop-up robots. The major problem today is obtaining a detailed and rapid damage assessment in a chemical, mine, and UXO threat. This is particularly true if mine and UXO neutralization depends upon weapon and fuse neutralization and aircraft continue to exhibit a low tolerance for rough runways.

Electronic Systems Division is taking the lead for the Damage Information Reporting System (DIRS). In its full configuration, DIRS would include an airborne-sensor, down-link, ground-based, computer-aided decision-support system to locate and assess damage, debris, mines, and UXO.

Operations

Airfield Construction. Robots are not yet used in construction by the military, although the civilian sector is beginning to develop this capability. Much of the major airfield construction today is contracted out by either the Air Force civil engineers or for major construction projects by the Army's Corps of Engineers. Wartime operations present a totally different set of emerging circumstances. Robots can reduce hazards to personnel and speed construction efforts.

Fire Fighting. A fire fighter can be better protected from the hazards of an aircraft fire and potential problems from unexpended and unexploded munitions by staying in an enclosed compartment. This protection can be achieved by keeping the fire fighter in a fire truck to operate the hose or spray equipment. The operator would need vision and dexterity capability to manipulate the equipment. Using an additional control to move a flexible boom with the spray nozzle, the operator could place the extinguisher chemical where needed. The European community has begun a major effort to develop fire-fighting robots.

Debris and Unexploded Ordnance Removal. The return of runways and other surfaces to serviceability following attack requires the removal of any unexploded weapons and debris so maintenance personnel can begin repairs. Robots should be used to move debris and unexploded weapons simultaneously without endangering life and to expedite the return of the base to an operating condition.

The Navy is the current DoD agent for explosive ordnance disposal (EOD) and UXO clearance, and the Air Force Engineering Systems Command (AFESC) has debris clearance responsibility. Because mines and UXO will be intermixed with debris, this division of responsibilities becomes antiquated and costly. The first EOD and mine clearance device to be fielded, called

ORACLE, is a special purpose armored bulldozer designed to withstand explosive charges while removing debris, mines, and UXO from pavement surfaces. Unfortunately, no method yet exists to satisfactorily clear mines in grassy areas or fields. Debris clearance remains a continuing problem that is under study and development at AFESC.

A major requirement is to develop a rapid robotic mine and UXO neutralization system. People are still needed to disarm large UXO and antitank-type mines. The biggest problem with mines, UXO, and debris is that developments in mine technology permit placing smart, selective targeting mines that can kill at a distance. These mines can destroy major portions of an airbase. The Army is developing such a mine, an extended range anti-tank mine (ERAM), designed to kill tanks at approximately 100 feet. Such a system, if designed for airfields, could kill aircraft, vehicles, and people. This problem is exacerbated because a mixture of time-fused bombs, antipersonnel bomblets, and mines dropped on an airfield would make current clearance systems useless. The clearance procedure then becomes labor-intensive, time consuming, and hazardous. Clearly, there is a need to locate, identify, and neutralize all types of mines and bombs, that use fuses, in all types of environments (debris, pavement, grass, snow, ice, and rain).

Rapid Runway Repair (RRR) and Facilities Restoration. Robots could begin repairing runways while hazards still exist from chemical or biological agents without exposing personnel. The robot vehicles would require remote vision and control from a safe habitat.

Currently restoration of runways, key facilities, and utilities is the responsibility of the AFESC and is of growing concern. The major problems that exist in RRR require labor intensive solutions in an all-weather and threat environment (mines, UXO and CBR). All the things said of mines and UXO removal apply. There exists today no capability to clear work sites for utility and facility repair without the use of people.

For RRR, a full range of smart construction equipment would reduce exposure of personnel to the threat environment and provide a capability to quickly return an airfield to an operating condition in the most severe environment (see **Figure 2-6**). If vertical take-off and landing/short take-off and landing (VTOL/STOL) aircraft become part of the Air Force tactical inventory, it is inconceivable that an enemy can deny sufficient pavement area to preclude takeoff and landing operations provided it can be reached. In the future, the problem will be to locate the needed amount of relatively undamaged concrete suitable for use as a runway, effecting necessary repair, and clear the way to *that location*. With VTOL/STOL aircraft, the attack center of gravity will probably move to smart bombs against hardened shelters and nuisance mining around the shelters. In this case, the role of robots would be the clearance of debris, mines, and UXO. For facility and utility repair, the problem of a potential CBR environment, mine and UXO hazards is accentuated because there is no program for clearing the numerous locations that airbase facility repair and restoration must address. Typical tasks are:

(1) Recovery of injured from damaged facilities, and

(2) Location, identification, and repair of pipelines (water, fuel and oil) electrical and communication systems.

Ground-based Radar and Communication Systems. The remote location of unmanned sites offers an excellent

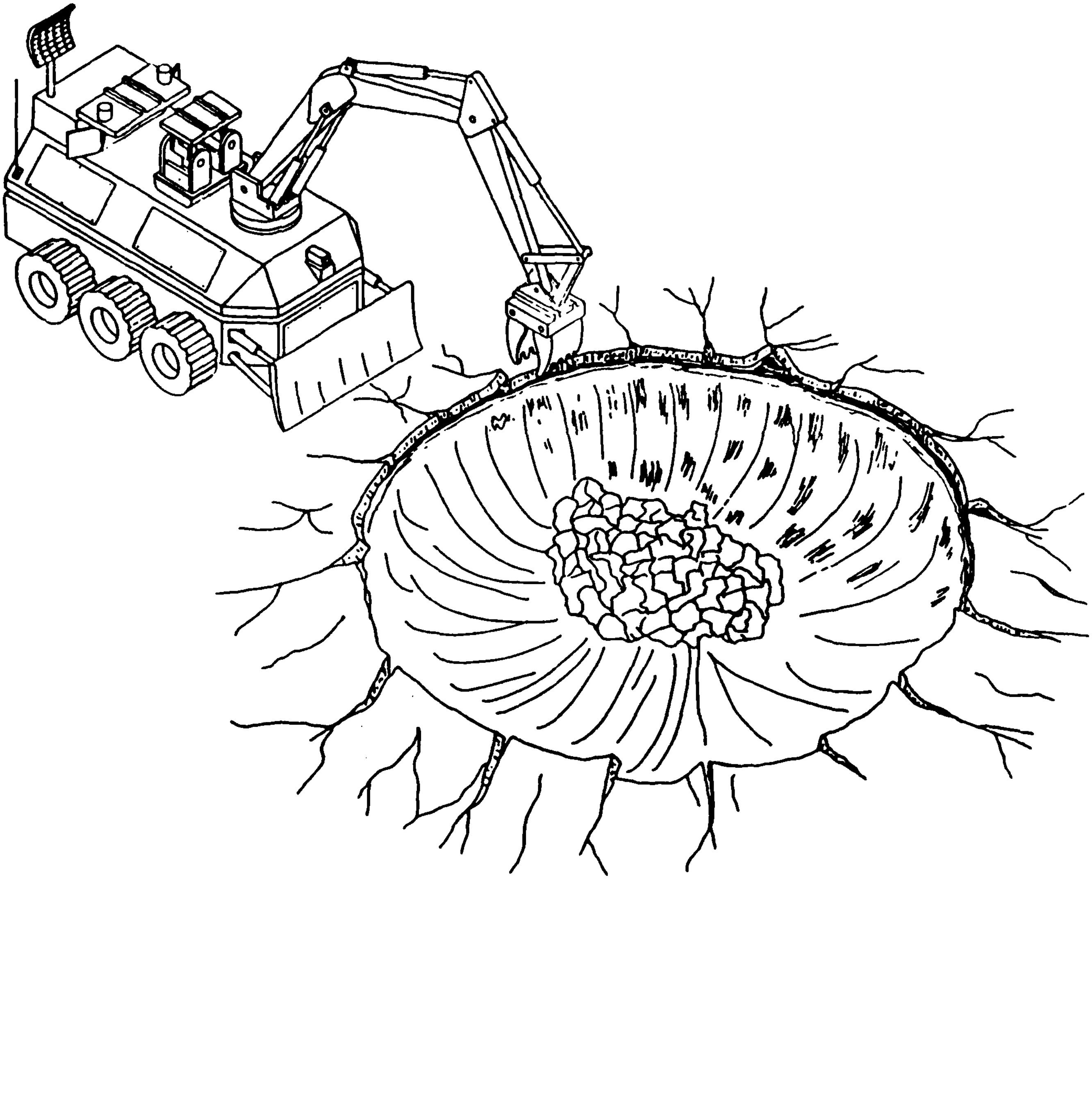

FIGURE 2-6 RUNWAY REPAIR ROBOT. Artist's conception of a repair robot filling in a bomb crater on a runway. [Courtesy Edward Alexander, HQ AFESC/RDCP, Tyndall AFB, Florida.]

opportunity for design considerations using autonomous repair. The ability of a site, with or without human intervention from afar, to diagnose problem areas, and to perform necessary repair or maintenance actions, should save system downtime as well as manpower and transportation costs. Site visit frequency would be reduced with only an occasional visit to replenish the necessary spare components. Self-repairing systems, or mechanical aids to self-repair, are ideally suited to increasing the service life of equipment at remote locations. Self-repairing systems would find applications in unmanned missile, radar, or communication sites as well as in space. The more difficult and expensive it becomes to place equipment repair personnel at the site, the more likely robots should be considered as an alternative, at least for a range of standard repairs. The success of a mechanically aided repair action is a function of the design of the equipment. Soldering or unsoldering critical electronic components is currently too difficult, but replacing components where the original design allows for ease of component replacement is practical. These features should be incorporated into the design of any remote site equipment. The Air Force should take appropriate action to ensure consideration of this application.

2.3 Robotics Application to Air Force Secondary and Support Operations

Air Force secondary or support activities have potential for robotics use. Many activities such as hospital services, food preparation, and construction are being addressed in the private sector to varying degrees, but currently at a much higher funding level than is available from the Air Force's limited resources. In the absence of a focal point in the Air Force, the benefits of this external investment may not be realized. These potential applications will be treated in subsequent paragraphs.

There are a broad range of applications that are peculiar to military operations, but which have multi-service applications, funding support, and in some cases commercial support. These applications include base and equipment security, fire fighting and operations during airfield attack.

Health Services

The processing of patients following a CBR attack is manpower intensive. A significant portion of the available personnel who survive the attack would be required to help process the patients. Moreover, these same personnel would be needed to perform cleanup operations and help prepare and launch aircraft. Robotic aids to the processing of patients would reduce personnel requirements and free them to perform other duties.

One future application that now deserves research activity is the use of tele-operated robots for microsurgery. This capability would enable critical operations in areas that cannot be reached by trained medical personnel.

Robots could have many uses in hospitals. First is the basic transport of material and supplies using guided vehicles. One application of robots used in commercial service that appears promising is their use in "fetch and carry" tasks. Now in commercial development is intelligent control technology that allows the vehicle to navigate without wires or floor stripes, avoiding obstacles, patients, and staff in the halls and elevators. Meals, supplies, and laundry, may be transported to nursing units in large carts while laboratory samples, X-rays, patient records, mail, and medication may be carried to and from the nursing units in small quantities. Such systems are in Beta test on

a commercial basis.

Second, support services in hospitals are also receiving attention in developing automation systems. Jobs that will be automated in the near future include meal preparation, dishwashing, laundry, inventory management, and floor and room cleaning.

Food Preparation and Service

Food preparation and service had limited review by the committee but offers possibilities for insertion of commercial technologies. The fast food industry has been interested in robot technology for over ten years. However, the problems of automating the functions of preparing and serving large numbers of meals, even of a limited menu found in typical fast food operations, has proven very difficult.

Several development projects now underway should produce results in about five years. In the next five to ten years, technology will develop to the point that the Air Force should consider automation in food preparation and service wherever support manpower is a major concern.

One future scenario would be an automated field kitchen that would be flown in and set up to support a base at a remote location. Another concept would be a semi-automatic facility at a permanent base that would be able to prepare a limited number of food and beverage items. This type of facility would be used in alert or combat conditions when around the clock, multi-shift operations were required. The system would be restocked during the prime day shift by regular personnel.

In the near future, meal transport and dishwashing are functions that could be automated and which would lower manpower requirements. Meal transport is an issue in any large meal service activity. The transport of meals and beverages to dining halls in coffee and meal carts, and the busing of dirty dishes all require manpower which could be better used in other areas.

Facility Cleaning

Air Force facilities include large areas that are cleaned on a regular basis. Facility cleaning also has possibilities for the use of commercial technologies. Commercial cleaning is the target of many active development projects in the United States, Europe, and Japan. Floor cleaning, particularly of tile floors, in large retail stores, malls, airports, and in hospitals is a repetitive and well structured job that is labor intensive. Commercial products are expected in the marketplace in the 1988-1990 time period. Mobile robots will be available that will reduce support manpower requirements in these cleaning functions. The problems in the commercial sector of recruiting and retaining competent labor to do commercial cleaning tasks dictates a rapid market acceptance once the technology is proven. A recent (1988) NSF-sponsored study on mobile robots, "Evaluation of Mobile Robots in Western Europe," cites significant accomplishments in facility cleaning operations by France and the U.S.

2.4 Maintenance, Remanufacture, and Modification

In the Air Force, major maintenance would be distinguished from minor maintenance by the degree of the activity requiring specialized skills, equipment or facilities. The work would be done at operational bases by depot "field teams." Many tasks can be done by humans and machines, rather than just by personnel with hand tools. The categories of tasks where machines could increase the

capabilities and efficiencies of the work force include: work in hazardous or undesirable environments, where physical strength is required, and tasks where repetitive actions are required. The deseal and reseal of the F-111 fuel tanks is an example of a time-consuming task in an undesirable environment. Machines would also enhance the speed and quality of inspection procedures and diagnostics, and augment wartime surge capability.

Maintenance includes many separate activities, some of which can be handled by robots. The heavy maintenance or depot workload certainly lends itself to an investigation regarding where robots could replace personnel in the work force.

Air Force Logistics Command Depot Maintenance

The AFLC's five major repair depots have numerous potential robot applications as summarized below:

- Hazardous Environments
  - Aircraft Painting
  - Component Painting - Automatic Paint and Process Lines
  - Aircraft Corrosion Treatment
  - Weapons Corrosion Treatment

- Manufacturing and Remanufacturing
  - Elimination of Heavy Jigs and Fixtures
  - Flexible Precision Machining

- Fabrication Tasks
  - Riveting, Deriveting
  - Welding
  - Cutting (Conventional, Laser, Hydraulic)
  - Composite Manufacture and Repair

- Precision Non-Destructive Inspection
  - Improved Diagnostics

- Assembly and Disassembly

Workload planning for the AFLC depots includes evaluating the economics of peacetime operations plus maintaining a wartime capability. The mix of depot activities will change with a reduction in major maintenance of aircraft, and an increased workload in components. This shift in workload requires a massive retraining effort for all personnel involved. The robotic portion of the workload should have a different and lesser problem of adaptation. Robots on a one shift operation can immediately be increased to a three shift, seven day work week: a fourfold increase in workload over the current one shift, five day work effort. Other programmable robots can be added to the component work force as an aircraft departs the depot for combat areas.

A major coordinated program has been established by the Materials Laboratory under the Manufacturing Technology (MANTECH) program, which unfortunately has experienced a substantive funding decrease in recent years. A thorough study of the robotic needs of each of the depots was conducted by Honeywell, and selected projects are being pursued through a joint effort of the Materials Laboratory, Headquarters AFLC, and the respective ALCs. Also, each center has one or more robotic projects in use in some area of depot repair. Although this is a significant effort, more projects have been identified than are currently being pursued. Additional activity is warranted and justified. Examples of the robotic tasks addressed in the Honeywell study include:

- epoxy removal
- shot peening/grit blasting
- engine assembly
- foam cutting
- radome stripping
- palletizing materials
- brake disassembly

- automated storage module
- wheel deburring
- box factory
- chrome plating
- bar code sorting
- alodining

The committee saw where robots could be used for selected applications in the depots. The more obvious applications included classes of work in difficult or hazardous environments such as painting, paint removal, and grinding operations. Other operations with an obvious potential for robots included those activities with large volumes of repetitive work such as turbine engine disassembly, rework and assembly, and wheel, brake, and landing gear overhaul.

Generally, the identified depot applications fall into two categories: (1) near-term applications using today's available robot technology and requiring only adaptation from manufacturing robots to maintenance and remanufacturing robots, and (2) the more beneficial but longer range robotic applications requiring additional research and development because no commercial manufacturing robots have the required capabilities. Light, flexible, mobile, modular robots do not yet exist, but they could provide the ultimate in wartime surge capability in depots. The Honeywell study primarily focused on near-term applications.

Hazardous Environments

Many depot work areas require the handling of hazardous or toxic chemicals or work in a hazardous environment. These areas offer a distinct possibility for automation. Some of the depots have begun robotic projects for painting, but many more opportunities exist where personnel should be removed from a hazardous environment such as:

- Aircraft Painting
- Component Painting
- Aircraft Corrosion Treatment
- Weapons Corrosion Treatment

Aircraft Painting. Aircraft normally are painted under controlled conditions at a depot. Paint stripping and repainting of aircraft, particularly in areas where accessibility is difficult, is labor intensive and contributes to aircraft downtime. Painting is also somewhat hazardous. For example, the painting of F-16 engine air intakes occurs at least every seven years. This task is a two-man job requiring three hours of sanding and two hours of painting in tight quarters. It requires someone to crawl several feet into the intake where cramped quarters and a lack of ventilation make it impossible for an individual to work more than a few minutes at a time. Because of the health hazard from sanding dust and polyurethane paint fumes, the engine must be removed -- a five-hour job for four people. The population of F-16 aircraft would keep a robotic paint spray system continually busy at a centralized facility. Alternatively, the robotic system could be transported and set up at different bases. Health hazards and distastefulness of the job aside, the economics should be attractive. Some special purpose application work is necessary, particularly with end effectors that must sand, wire brush, and sand blast, and then take up a paint spray gun. Naturally, with a robot arm in the intake there would be no need to remove the engine. The ideal arm would be of the multi-articulated snake type. Arms with conventional architectures, however, probably would not be able to traverse the entire air intake.

Aircraft painting at the AFLC depots is primarily for the purpose of corrosion protection and prevention. It is a slow process. The painters move from scaffold to scaffold, spray painting

by hand. The quality of the painting effort is a function of the skill and capability of the operator. If the paint layer sprayed on the aircraft is too thin, then inadequate corrosion protection is applied; if the paint is too thick, then unnecessary weight will be carried for the next several years thereby wasting fuel. Massive ventilation systems must be installed to protect the operators from the paint fumes. Finally, the exhaust, paint residue, and cleanup materials following the painting operation, must be processed in accordance with Environmental Protection Agency (EPA) standards, which frequently change and usually become more restrictive and therefore more costly.

An opportunity exists, through the use of robots, to remove personnel from the painting environment, to uniformly apply the paint for the correct protection, and to reduce the fumes and cleanup operation that results in the accumulation of hazardous chemicals.

Component Painting - Automatic Paint and Process Lines (APPL). Painting components to prevent corrosion has always been labor intensive. Some depots have begun small programs to add a robotic capability and have experienced limited success. Problems with worker hazards, EPA sanctions, and hazardous waste removal are identical to those in aircraft painting.

Since a capability to paint components is required at each depot, the opportunity exists to develop a good robotic paint process for components. A robotic component paint system would speed the process, give improved quality to the operation, remove the workers from the hazardous environment, and reduce the hazardous waste problem. Also, a robotic system would give added capacity for processing more components during wartime.

Painting robots have been available for several years and have generally performed acceptably. However, the islands of robot use are less than optimum when considering the potential of a fully automated APPL where cleaning, chemical treating, masking, painting, de-masking, inspection, and packaging would be done within a fully integrated facility. Each component would be coded and the data base would route the component to the proper APPL cells dictated by the processing specifications resident within the data base. (See **Figures 2-7 to 2-12.**)[1]

Aircraft Corrosion Treatment. The treatment of corrosion on aircraft frequently requires the application of toxic chemicals. Robotic application of these chemicals would largely remove personnel from the toxic environment, and would ensure a more uniform application of the treatment.

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[1]Figures 2-7 to 2-10, 2-12 to 2-18, and 2-20 to 2-28, and the substance of their captions are from *Robotics Application Study for Air Logistics Centers*, Honeywell, Inc., January 1987, Air Force Wright Aeronautical Laboratories, Materials Laboratory. We have used these figures because several potential applications that we cited were described in the Honeywell report and these are the only available depictions of them. These figures are artists' conceptions of systems that have not yet been built and for which there are no photographs or other representations.

The precision inherent in robotic application and the ability to work directly in a toxic environment will significantly reduce the amount of toxic chemicals. The use of robots will also reduce the cost of disposal of the toxic chemicals, which is becoming a major driver in the cost of heavy maintenance of aircraft. The improved precision of the chemical treatment should improve the quality of the corrosion treatment, provide for a longer interval between corrosion treatments and thereby increase the number of active aircraft available for operational use. This application can become a small force multiplier for aircraft.

Weapons Corrosion Treatment. Conventional weapons are stored for long periods at various locations. Many of the locations are in close proximity to salt water and the weapons require periodic corrosion removal and repainting. The application is highly repetitive and there is some hazard working with corroded weapons. Robotic removal of the corrosion would lessen the danger to personnel, and save manpower from doing dull, routine, and undesirable tasks. Robotic application of the paint following corrosion removal would help apply the corrosion preservative in a more uniform manner and decrease the requirement for reapplication.

This application is an example of heavy maintenance that should be done at remote locations. It is considerably easier to move the robot to the weapons storage location than to move all the weapons to a depot.

Remanufacturing

Remanufacturing is similar to maintenance in regard to the technical requirements for robotics and automation. Remanufacturing robot programs funded by DoD tend to lead technology but are only a small part of the application of robots to military manufacturing. A majority of such developments have been funded by robot manufacturers and most of the practical application of robots to manufacturing has been achieved by them.

Robots can be used as transfer devices, in forming operations, for assembly and finishing, and inspection. Transfer robots move parts from one part of the factory to another, typically on automated guided vehicles (AGV), or they load and unload other automatic machines in the factory. Robots also can be used in forming operations, provided that only modest forces and low precision are required, as in deburring, grinding, and sometimes in drilling. (See **Figures 2-13 to 2-18**.) Robots can also assemble a product and apply a finish. While robots have been widely used to weld, paint, and perform inspection operations, assembly often requires dexterity and the application of delicate forces not readily available in today's robots.

The Air Force has not been the major military funder of robotics development in the manufacturing area. The Intelligent Task Automation (ITA) program, funded by the Air Force Materials Laboratory (AFML) at Wright-Patterson Air Force Base and DARPA, is demonstrating the application of vision to inspection, control of precision operations through vision and tactile sensing, visual identification of parts (even with a cluttered visual field), and automatic development of a detailed plan from identified goals. Two separate systems are being developed for the AFML to demonstrate flexible assembly of airplane bulkheads. The concepts from ITA and the flexible assembly systems will be applied to an Automated Airframe Assembly Center (AAAC) for the AFML. The Navy has funded several smaller robotic manufacturing projects, such as laser welding and cutting systems, a

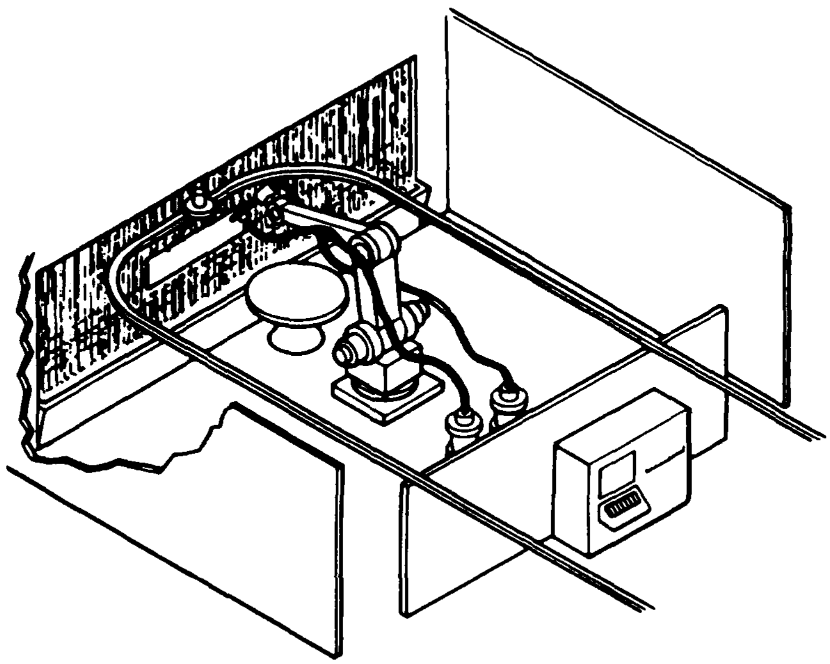

FIGURE 2-7 SMALL PARTS PAINTING. When a part is ready to be painted the operator mounts it on the conveyor system, tells the robot controller where the part is and what processes should be performed. The part waits on the conveyor until the parts ahead of it have been processed. Before a part is scheduled into the paint booth, the cell controller checks to see what process is to be performed on it and if the robot has the proper end effector currently mounted. If it does, the part is moved into the paint booth and the part is painted. If the robot does not have the right paint for the component, it tells the operator to mix up a small batch of paint for that item. Then when the items is moved into the booth, the operator mounts the new paint gun on the robot.

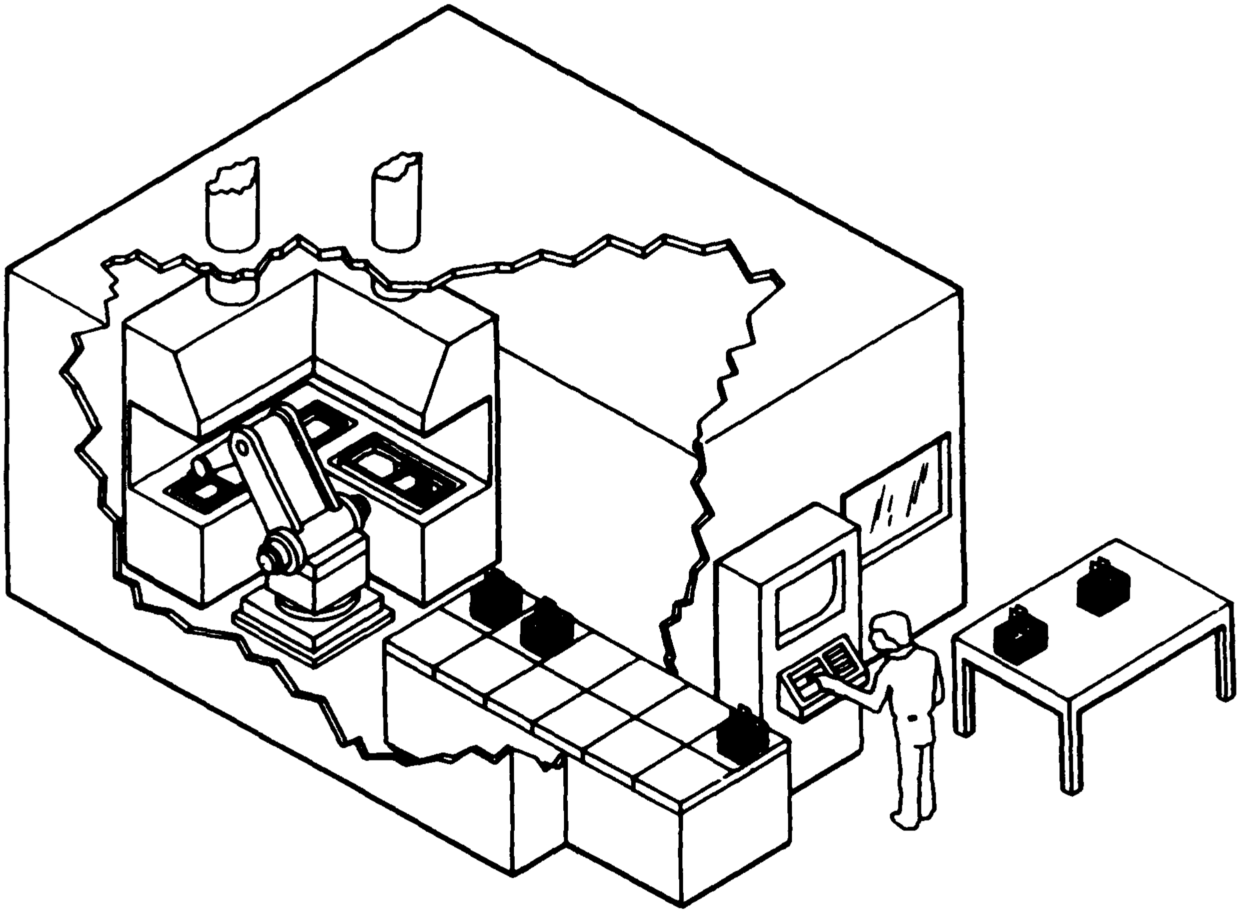

FIGURE 2-8 AUTOMATED EPOXY REMOVAL SYSTEM. Components are put in baskets, then put on the material-handling system. The operator tells the cell controller what operations are to be performed on the components. The robotic system automatically sequences the components through the chemical baths and rinses with the desired soak times. When the basket of components is finished, it is put back on the material-handling system and taken out of the hazardous environment back to the operator. The operator can then inspect the components and ship them back to the appropriate work stations.

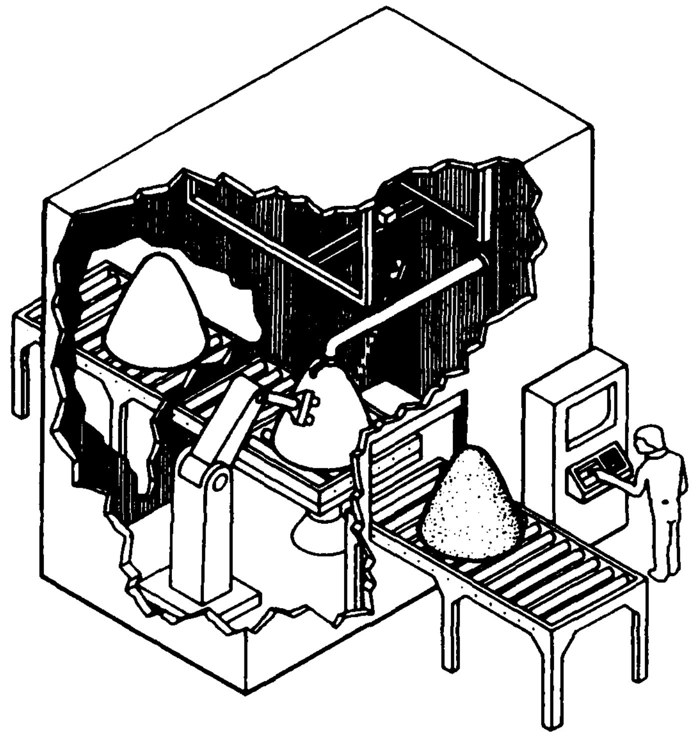

FIGURE 2-9 RADOME PAINT STRIPPING SYSTEM. The radome is automatically moved to the first station. The radome is slowly rotated while a laser etches the paint down to, but not including, the primer level. The laser could potentially etch the radome into a grid with areas 2 inches square or less. Once etched the radome moves to the paint remover shower where it is sprayed until the primer beneath the paint is loosened. Once the paint is loosened the dome moved to the robotic station where the robot removes the paint from the surface. Once the paint is completely removed the radome is moved from the cell.

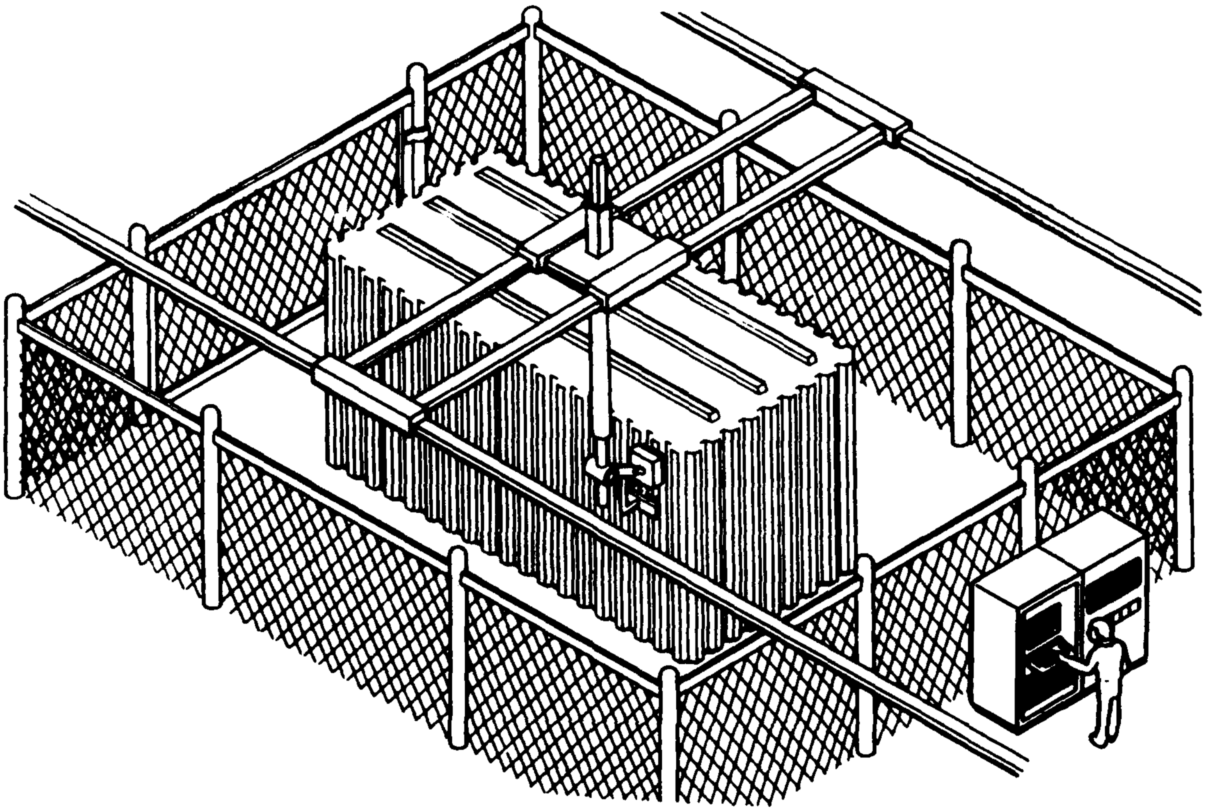

FIGURE 2-10 AUTOMATED ALODINING SYSTEM. The van (or shelter) is parked in the middle of the alodining facility. The automatic alodining equipment is primarily a gantry robot mounted above the work area. The operator starts by taking a control pendant and instructing the robot control system on three or four points to identify where the van is located. The operator then leaves the safety area and starts the process.

The robot end-effector is equipped with spray nozzles for water, phosphoric acid, alodine, rotating Scotch Brite brushes, and a vision system. The process starts by completely soaking down the van. The computer system software partitions the van and the robot proceeds to spray phosphoric acid on a given section. The brushes move into position and agitate the phosphoric acid on the van surface. The vision system monitors the process until it turns golden in color at which time it starts to rinse off the remaining alodine. These steps are repeated until the entire van is processed.

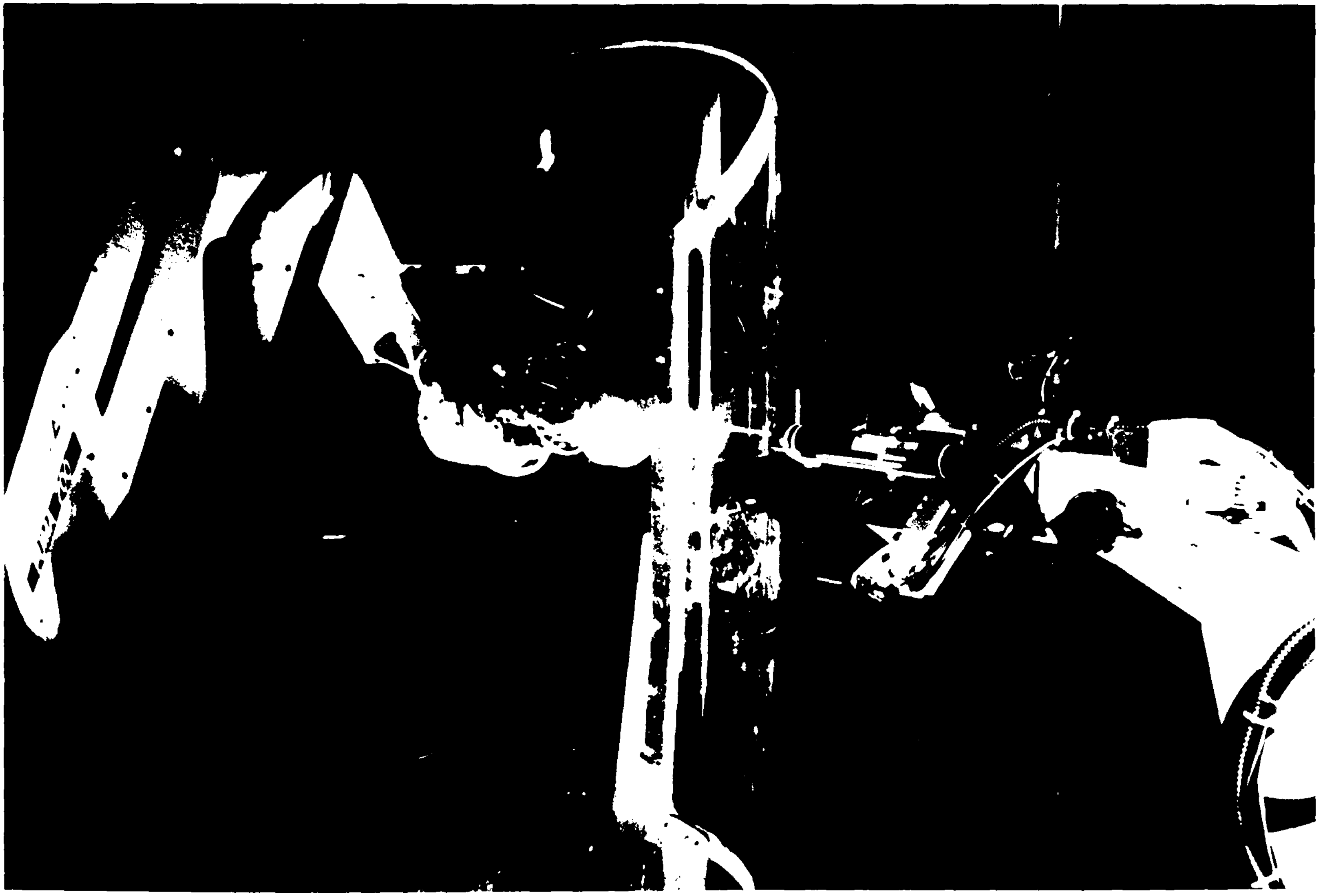

FIGURE 2-11 ROBOTIC POLISHER FOR COCKPIT CANOPY. A robotic polisher for the cockpit canopies of high performance aircraft uses an advanced robot cell control architecture and uses machine vision technology to perform canopy inspections. Locating and polishing to optical quality a wide range of canopy flaws involves intelligent image recognition and adaptive controls. The photograph shows an early working prototype of the system. A full-production system, employing two independent polishing robots serviced by a common inspection robot is being fabricated. [Courtesy Douglas L. Michalsky, Robotics and Automation Department, Southwest Research Institute, San Antonio, Texas.]

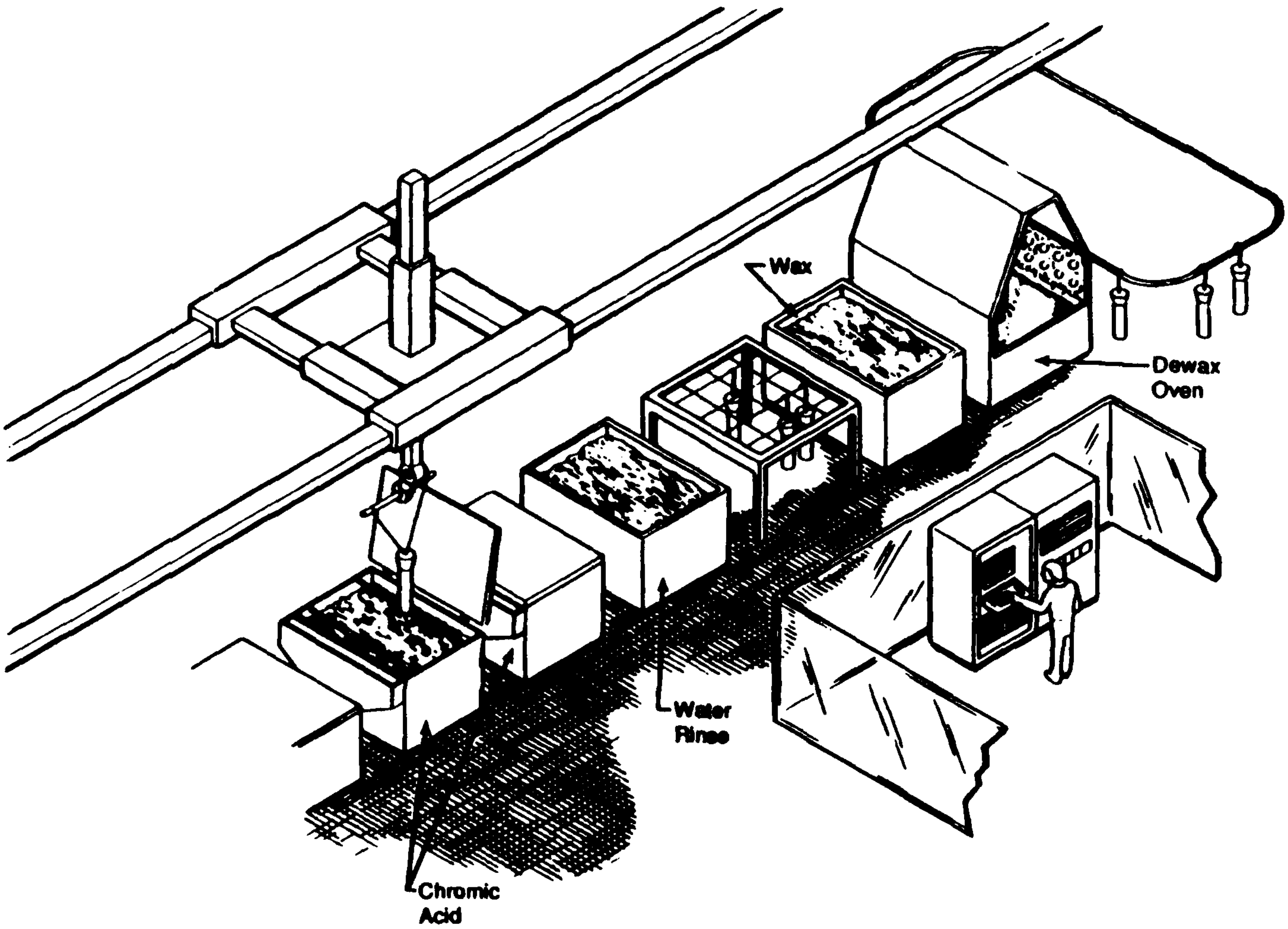

FIGURE 2-12 AUTOMATIC CHROMIUM PLATING LINE. The operator places the part, hanging from a fixture, in the pick-and-place stand. A probe will check to see if the part is waxed or not. If not, the robot proceeds to cycle the part through the waxing operation. When the waxing is done it is brought back to the pick-and-place stand where the operator manually finishes the tape removal and other chromium plating preparation operations. When the operator is finished preparing the part, it is again placed in the pick-and-place stand as before. This time the probe senses that the object is waxed and is ready for plating. The operator inputs the part number and the system then schedules the tank and sets the rectifier parameters. The robot moves the part to the tank, the top opens and the part is hung on the cathode. The tank top is then closed and the plating process starts. The only time the tank ventilation equipment is required is for some minimal time before the tank is opened and while it is open. If process control requires it, the part is removed and measured to identify the plating rate. These data are gathered by the cell controller and the plating parameters are adjusted to suit.

Once the operation is complete the computer stops the plating operation, the robot moves the part to the rinse tank and then to the wax removal oven. The operators receive the part as it exits the oven and the manual cleaning operations are then performed.

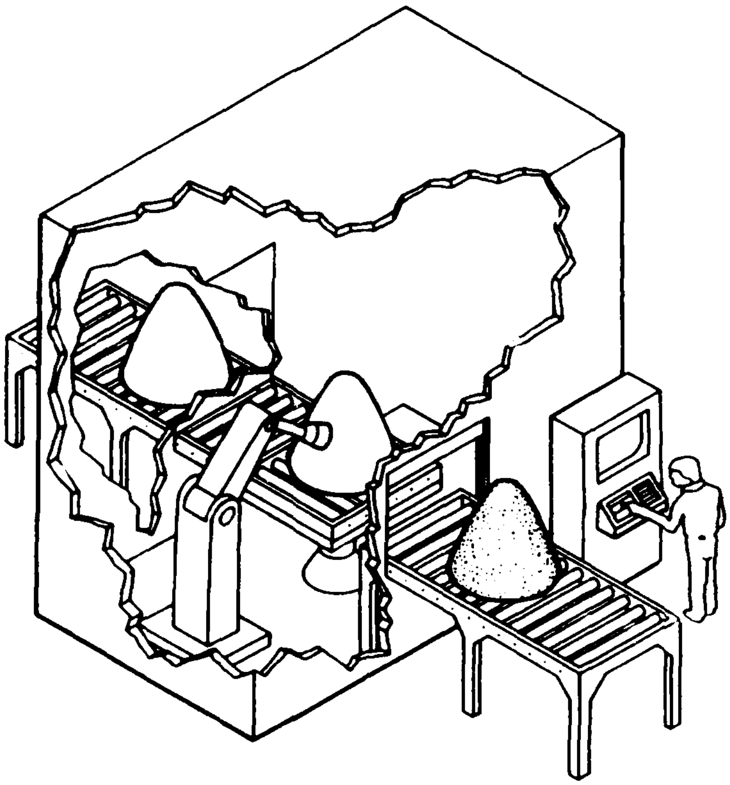

FIGURE 2-13 RADOME SANDING SYSTEM. Radomes are placed on a turntable capable of 360-degree rotation. Once the radome is in the sanding station, the robot begins sanding in the up-down direction. The turntable slowly rotates to permit sanding of the entire surface. When sanding is used as a patch paint removal operation, a vision system is used to locate areas requiring sanding. Force sensors are used to apply appropriate force on the sanding element.

Material handling equipment associated with this cell consists of a conveyor line to carry the radomes to and from the sanding station. Once the radome is placed on the conveyor, it moves through the sanding station without human assistance. The only operator input required is to indicate the type of radome (C-130 or C-141) and sanding operation (paint removal or paint preparation) to be performed.

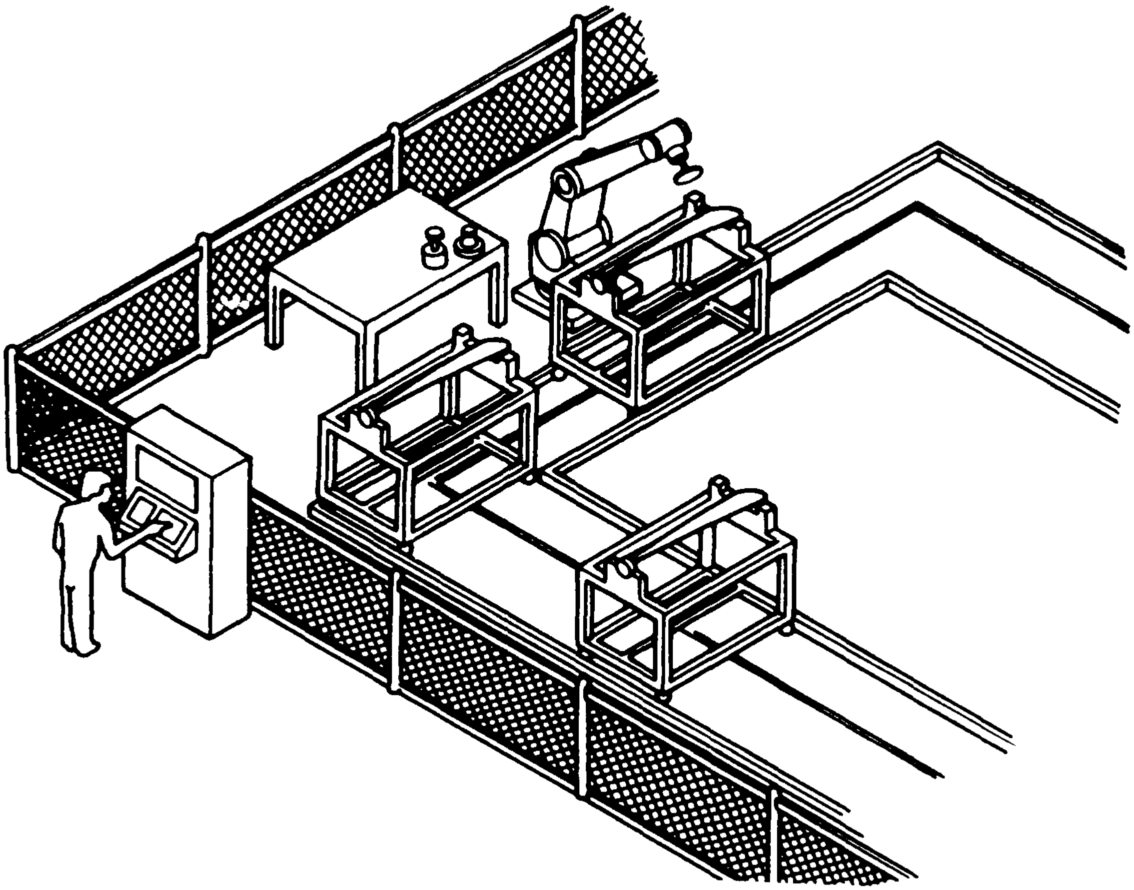

FIGURE 2-14 C-130 PROPELLER GRINDING SYSTEM. Blades are mounted on the racks and attached to the automatic material handling system. One a first-in-first-out basis they are moved into the grinding/polishing station, where they are mounted in a fixture and positioned for grinding. The robotic grinder grinds the blade using successively finer abrasives. The vision system locates nicks and corrosion pits and provides input to the controller, which controls the time and force of the operation. The blade contour and width are monitored continuously and can be provided in printout form if required. Since the contour and width are available at all times, no separate gauging station is needed.

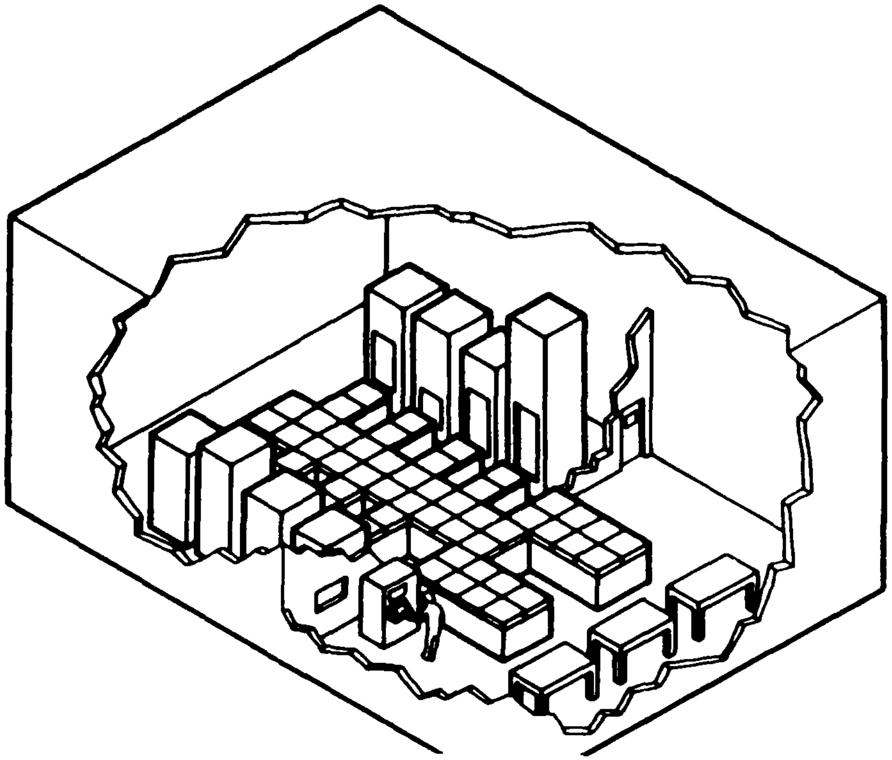

FIGURE 2-15 AUTOMATED SHOT PEENING AND GRIT BLASTING SYSTEM. When an item or batch of items are received they are taken to one of the part preparation stations. Here the operators gather the fixtures and masks for that particular part and mount it and its fixtures on a material handling system pallet. This pallet is manually transferred from the part preparation area to the input queue of the material handling system. There the operator enters the part ID number into the computer. The cell controller takes control of the part, figures out the sequence of steps to be performed on the component, and schedules it at each of the appropriate machines. The cell controller uses part, machine, and system characteristics to optimize the machine utilization time, and minimizes set up time and flow time for each part in the system. When a part is finished or needs to be remasked, the material handling system delivers it to the output queue, where an operator transfers it back to the part preparation area along with its paperwork. The operator either remasks the part or removes the part and its fixtures from the material handling system pallet, sends the part to its next operation, and starts on a new part.

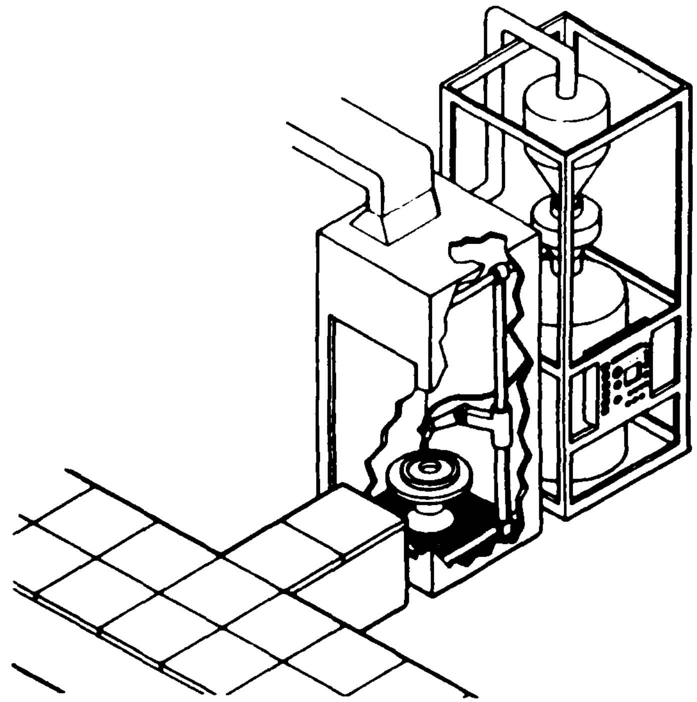

FIGURE 2-16 AUTOMATED SHOT PEENING AND GRIT BLASTING SYSTEM (Close-up View).

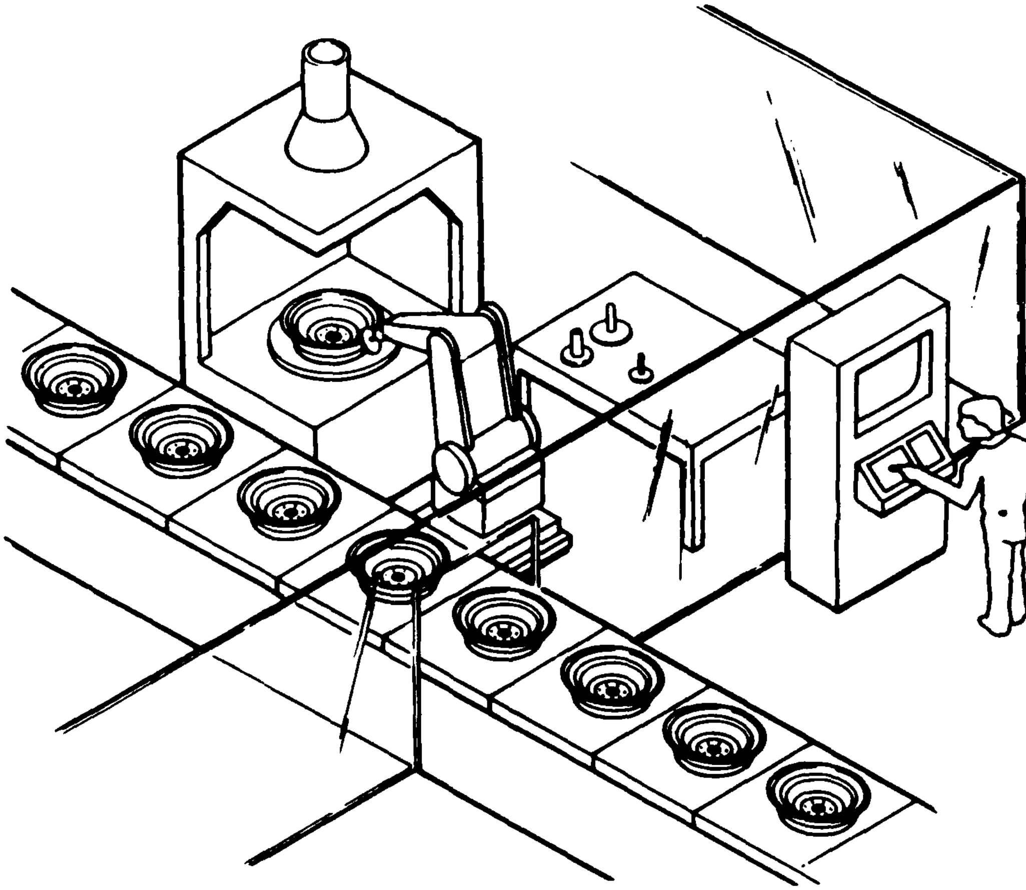

FIGURE 2-17 WHEEL DEBURRING SYSTEM. Automating the open loop sanding would automate at least 80 percent of the deburring now being done manually. Initially, one of these deburring workcells should be installed with this system to deburr several of the larger aircraft wheels. As the system becomes more reliable, more wheels can be added to its capacity.

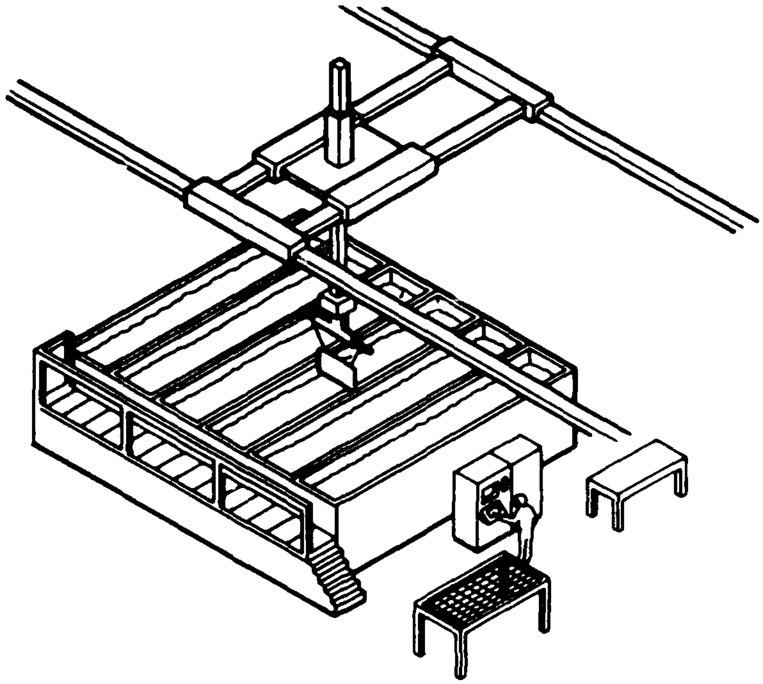

FIGURE 2-18 CHEMICAL MILLING AUTOMATED SYSTEM. Parts to be chemically milled or cleaned are mounted on the overhead gantry robot. The operator tells the robot what processes go through and the dwell time for each process. Also, if a part needs to be tapered, the operator can set the rate at which that part is removed from the etchant. Any time a part requires in-process inspection, the robot brings the part out of the hazardous environment back to the part preparation area where it can be inspected, redoing processes as needed.

propeller welding system, and a large noncontact parts profiler.

The National Institute of Standards and Technology (NIST) has built an automated manufacturing research facility (AMRF) where it is developing communication standards, learning to organize robotic control functions and to control the manufacturing processes. The AMRF efforts are applicable to military problems. The Air Force would benefit from the reduced costs that may be achieved by robotic manufacturing.

The Air Force should be particularly interested in robotic manufacturing of airframes, which are large, light-weight structures. The Navy shares this interest. If robotic operations can perform a complex range of light machining tasks without supporting jigs, it can reduce the need for an inventory of expensive jigs and fixtures, thus achieving substantial savings.

Over the past decade, the aircraft industry has sought to decrease the cost of aircraft components through automation and robotics. The process has been tedious, expensive, and sometimes unsuccessful. Robots have been placed in aircraft factories with mixed results, primarily because of a lack of integration (even though the robotics industry is generally considered mature enough to supply reliable, cost-effective systems) but also because a significant number of aircraft are not being built each year. The keys to success appear to be proper analysis, planning, and implementation. Experience indicates that without thoroughly understanding the manufacturing environment, the impact on overall peripheral systems and processes, the return on investment and the intangible benefits of the system, the chances of successful implementation are slight.

The state-of-the-art manufacturing process is represented by a tightly woven, well-integrated process for building a product. It begins with an idea, progresses through engineering development, and ends in production. Any new technology, such as robotics and automation, may be integrated into the overall manufacturing process only after a thorough evaluation of the process has indicated definite, justifiable benefits that warrant the resources required for implementation.

Robots are generally thought to be mature enough for use in factories for simple functions without major Air Force efforts in the development of robots proper. The major efforts should concentrate on future generations of robot technology with emphasis on the total integration of manufacturing systems.

Elimination of Heavy Jigs and Fixtures. Any component change or modification which requires changes to the jigs or fixtures is slow to be implemented in the manufacturing environment. After the component is redesigned, then the jigs and fixtures must be redesigned, followed by modification to the jigs and fixtures. The jigs and fixtures must be measured and verified before the actual component modification can begin. Robotic manufacturing with sensory perception can sometimes eliminate the jigs and fixtures, or reduce the requirements to standard (or flexible) holding fixtures that do not require change when the components being held are changed. A change can be made as fast as the robot can be reprogrammed to accommodate the change. This approach should become standard practice in CAD/CAM designs of the near future.

Flexible Precision Machining. Flexible precision machining goes beyond the elimination of jigs or fixtures. Light structures, as used in aircraft and missiles, can be machined with the precision accommodating the force

deflection of the machining tool and the component being machined. Without the sensory feedback of the machine force and location, and the knowledge of the deflection properties of both the item under manufacture and the robot itself, the precision desired will not be possible. The next step should allow for critical parameters to be maintained without the return to heavy-jigs and fixtures to reduce deflections to allowable levels. A robot's flexible precision machining capability will allow the AFLC depots to manufacture practically any component on demand, with minimum setup and operating time. Items needed for any contingency can be rapidly manufactured, or a design change can be incorporated into the process with virtually no lost production time. Wartime surge would follow a significant economic peacetime operation.

The Air Force tries to buy engineering data for all items being acquired so that the items can be manufactured or procured later. The Air Force buys large, expensive items during production that will probably never be used, but are "insurance" should the need arise. The items that are manufactured require massive jigs and fixtures to give the proper alignment and precision to the manufacturing process. The jigs and fixtures take weeks or months to construct or align. They are bulky, and it is impractical to build and store all the jigs and fixtures that may be required. Consequently, when requests are generated for the manufacture of components, it is frequently a long period before the end item is manufactured.

Developing a robotics capability for light flexible manufacturing would provide the Air Force the opportunity to reduce significantly the requirement for expensive jigs and fixtures. This process would require sensing the flexibility of the material being worked, the flexibility of the machine doing the work, and compensating for the respective deflections so the final process has the precise dimensions required. A programmable, flexible capability would replace the slow expensive process of massive jigs and fixtures and would reduce or eliminate the requirement to buy "insurance" items. A modification to a component or part that requires setup changes can be very slow when the tooling must be redesigned, manufactured, and aligned. The same modification can be handled by robots with only minor changes in the manufacturing instruction "program." A wartime capability is added by throughput productivity, and reduced response time for changes deemed necessary at the time.

The elimination of the major setup costs of the tooling, and the increased productivity of having items shortly after they are required, coupled with the probable elimination of the "insurance" item purchases, makes this a highly attractive application.

Fabrication Tasks

Where tasks are repetitive, the commercial manufacturing robots can be beneficial if the tasks have considered a design which provides for automation. Many of the current tasks in the AFLC depots fall into this design for automation category. Future design of Air Force systems should include the consideration for mechanical aids in the maintenance and repair of components.

Riveting and Deriveting. The Air Force and the Navy have investigated the possibility of robotic removal and installation of rivets in aircraft structures. This periodic riveting is time consuming, and the human is less than precise in removing the old rivet. Frequently the removal operation damages the parent material requiring the installation of an oversize rivet. Each time an oversize rivet is required, more of the parent material is removed,

reducing the basic strength of the item. Robotic riveting and deriveting have demonstrated it is possible to allow the robot to precisely locate the rivet, and remove it without additional damage to the parent structure on a relatively flat and rigid structure. In a like manner, the robot can precisely locate the hole and install the rivet with consistent quality, thus eliminating the probability of the rivet becoming loose and requiring reinstallation at a later date. The use of robots in this application can increase reliability and decrease maintainability requirements.

Welding. Robotic welding is commercially available and used in vehicle manufacturing. This application can and should be expanded to include robotic welding of aircraft materials to aircraft and missile tolerances.

Cutting. The cutting of components is also a task that is commercially available for vehicles, components, and other commercial applications. The commercial efforts need to be enhanced to allow for robot cutting of aircraft and missile materials to required tolerances. Robot cutting should include any form of cutting such as conventional, hydraulic or laser. The precision capabilities of robot operations should increase the quality of the items being cut by reducing the variation in the size and shape of the components.

Composite Manufacture and Repair. In the manufacture of composite components, the repetitive applications of fibrous materials and resins is well suited for automation. A programmable robot should be developed to alternate activities, adding precision and quality to the process, and significantly reducing manufacturing man-hours and time.

Repair of composites begins with non-destructive inspection and removal of any damaged or deteriorated areas. The area is then repaired by rebuilding with alternating layers of fibers and resins. These tasks can be done by robots and with improved quality and efficiency.

Precision and Non-Destructive Inspection

Various tests by the Air Force and other activities have proven that the results of manually operated non-destructive inspection (NDI) equipment produces results that are heavily influenced by the performance of the operator. Significant variances in performances exist between operators, and even between the same operator over time. Robot operation of the equipment could reduce the variability in performance testing and improve the quality of the tests. Two major mistakes are made by operators: (1) faults are missed and faulty components are passed on as acceptable, which jeopardizes safety and mission performance, and (2) acceptable components are labeled as faulty. Correcting these false alarms wastes man-hours and increases system downtime. Robot application and control of the movement of the sensors would significantly reduce both types of errors, increase reliability and decrease aircraft maintenance downtime. (See **Figures 2-19 and 2-20**.)

Current diagnostics at the depot exhibit the same problems as the operational units. Components that have failed or where failure is imminent go undiscovered, and faulty components are "found" where none exist. Many of the components that are returned to the depot from operational units are tested and returned with no repair activity because no malfunction was found. It is unknown whether the error in the analysis of the component was a false alarm generated by the operational

activity, or a failure of the depot to detect the fault in the component. All that is known from this evaluation is that the component was removed from service, moved to a depot, required time on the depot tester, and was moved to another operational unit. In addition, there was time lost in the packaging and handling of the component by supply, transportation, and maintenance personnel at each location.

Robotic testing would reduce the variability of the testing procedure and improve the quality of the tests. Robotic measurements combined with learning algorithms should greatly reduce current problems.

Assembly and Disassembly

Component assembly and disassembly are highly repetitive tasks that can be handled better by machines than men. Examples of heavy volumes of activity even in peacetime include landing gear wheel and brake assemblies and aircraft engines. (See **Figures 2-21 to 2-23**.)

Aircraft wheels and brakes wear out in the normal course of aircraft operations. They need major maintenance on a recurring basis. The Ogden ALC is the repair center for all Air Force wheels and brakes. Ogden ALC processes thousands of sets of wheels and brakes per year. A major multi-building complex has been established for this one specialized purpose. Most of the wheel and brake assemblies are comprised of hundreds of parts, which must be disassembled for inspection and rework, and eventually reassembled in final processing. This activity is labor intensive and slow.

Application of robots to this task would speed up the process and improve the quality by doing the repetitive tasks of disassembly and reassembly. This application will reduce the time that items are in the repair pipeline and in turn reduce the number of spare wheels and brakes that are required to be purchased just to fill the pipeline. A significant manpower savings is possible and the wartime capability for increased workload would be enhanced.

Commercial assembly technology is available for some of the operations and this technology should be readily adaptable. The current design of the wheels and brakes do not include ease of disassembly and reassembly using automation tools. Technology would have to be improved for additional functions. The cost/benefit ratio is high. The repetitive nature of the tasks and the volume of business make this an excellent application to pursue. There should be applications similar to those of the Air Force for commercial aircraft.

The Air Force owns and uses about 50,000 turbine engines that are subjected to wear and breakdown during their operational use. They require major maintenance based on individual design and usage and are processed through the depots several times during their lifetimes. The Air Force engine repair depots at Oklahoma City and San Antonio refurbish thousands of engines each year at great cost.

Robotic and automation aids could do some of the repetitive disassembly and reassembly tasks. Each engine must be disassembled for repair, sometimes totally disassembled. The series of tasks to each level of disassembly are repetitive and lend themselves to some form of programmable robots. The repetitive tasks and the volume of business make this attractive. A limited commercial base is available to use.

To date, robot systems operate on an open-loop relative to process-generated force disturbances and therefore must be supported by jigs and fixtures to achieve the level of precision

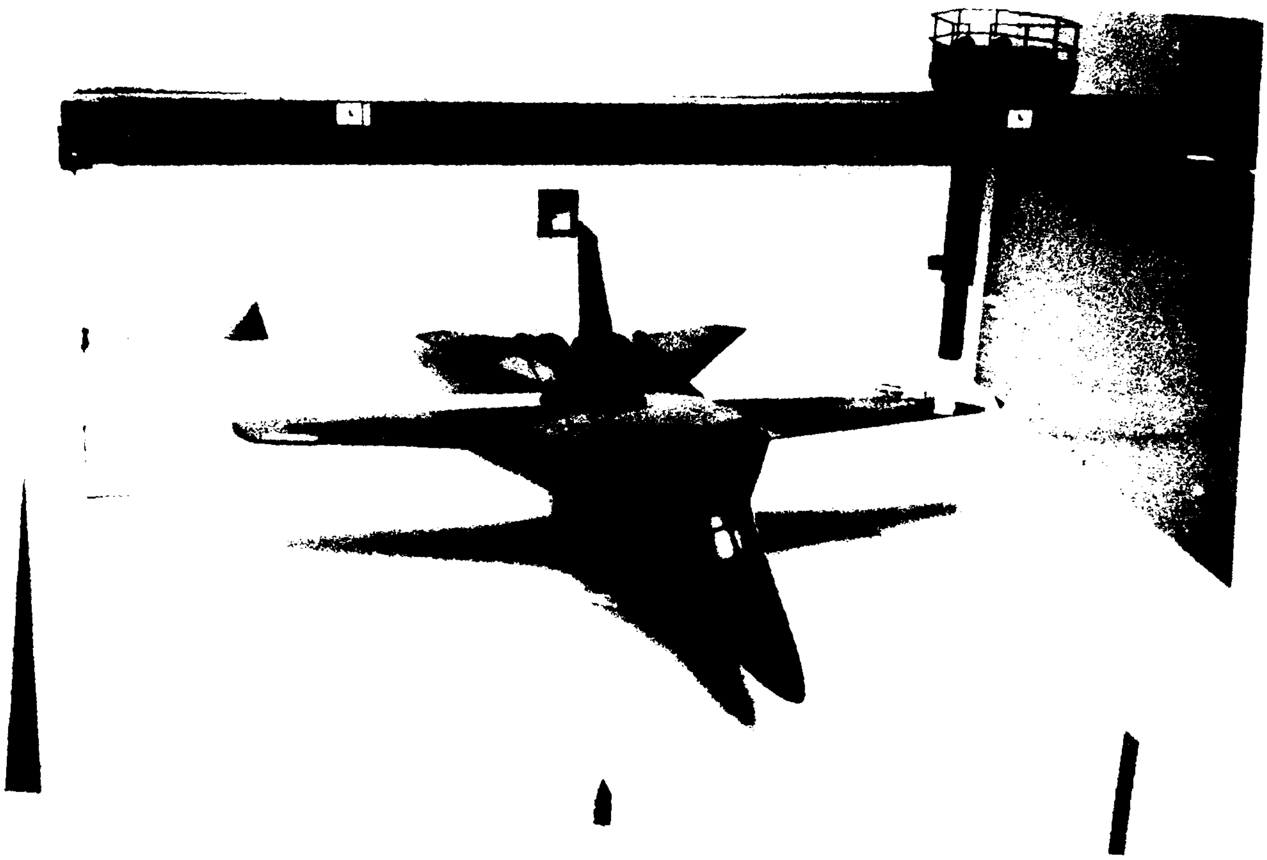

FIGURE 2-19 NDI ROBOT INSPECTING AIRCRAFT WING (MODEL) [Courtesy Margaret Eastwood, CIMCORP Inc., Aurora, Illinois.]

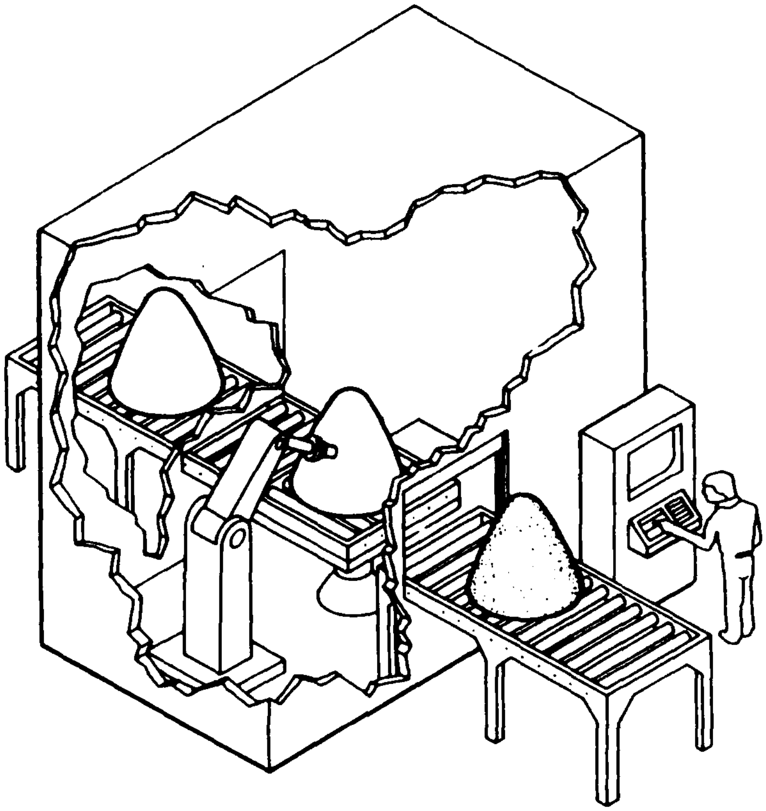

FIGURE 2-20 RADOME INSPECTION SYSTEM. The system uses a robot with the appropriate test equipment to scan the complete area of a radome. The system could either prepare a map of the radome showing the damaged areas or preferably mark the dome directly. The check for lightning damage may need some manual assistance.

The N-Ray is the best piece of equipment to use to locate water in the radome because it has a superior ability to spot water and in most cases will also identify the delamination (caused by water). To further test for additional areas of delamination, if required, ultrasonic testing can be used, or mechanical tapping can also be used. A device to repeatedly tap the surface can be fitted to the robot arm, and the acoustic signature detected and analyzed continuously. Both of these tests can provide consistent, accurate, and predictable results. This feature can address the concern that operators may currently be overly liberal in marking bad areas, causing areas to be repaired that are not actually in the failure mode. Where this is the case, the results are higher repair costs and premature aging of the radome.

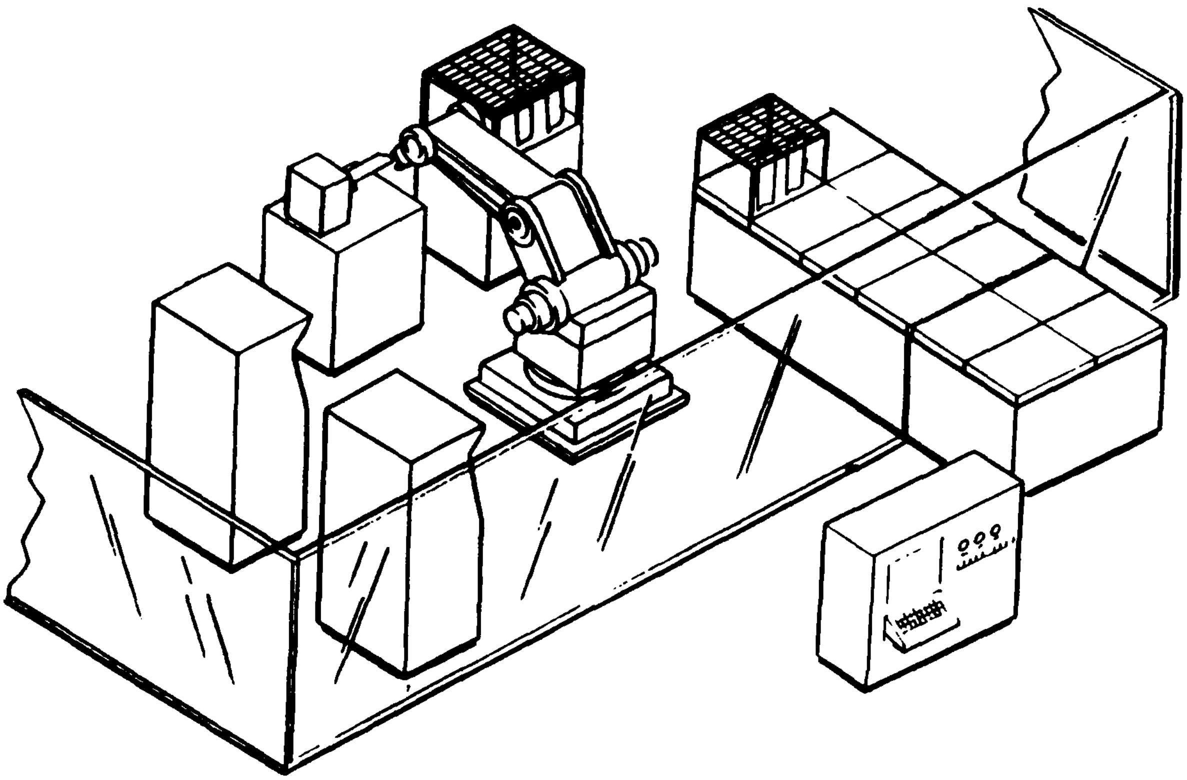

FIGURE 2-21 F-100 INLET FAN MODULE BLADE ASSEMBLY SYSTEM. The robotic system can balance, classify, and mark each of the blades before it puts them into a holding fixture. When all the blades in a set are finished, the robot controller sorts the blades so that opposing blades are balanced and then commands the robot to put each blade back in its sorted position in the initial storage rack.

In the second phase, the blades are automatically inserted into the disks, leaving inspection and air seal insertion to the technicians.

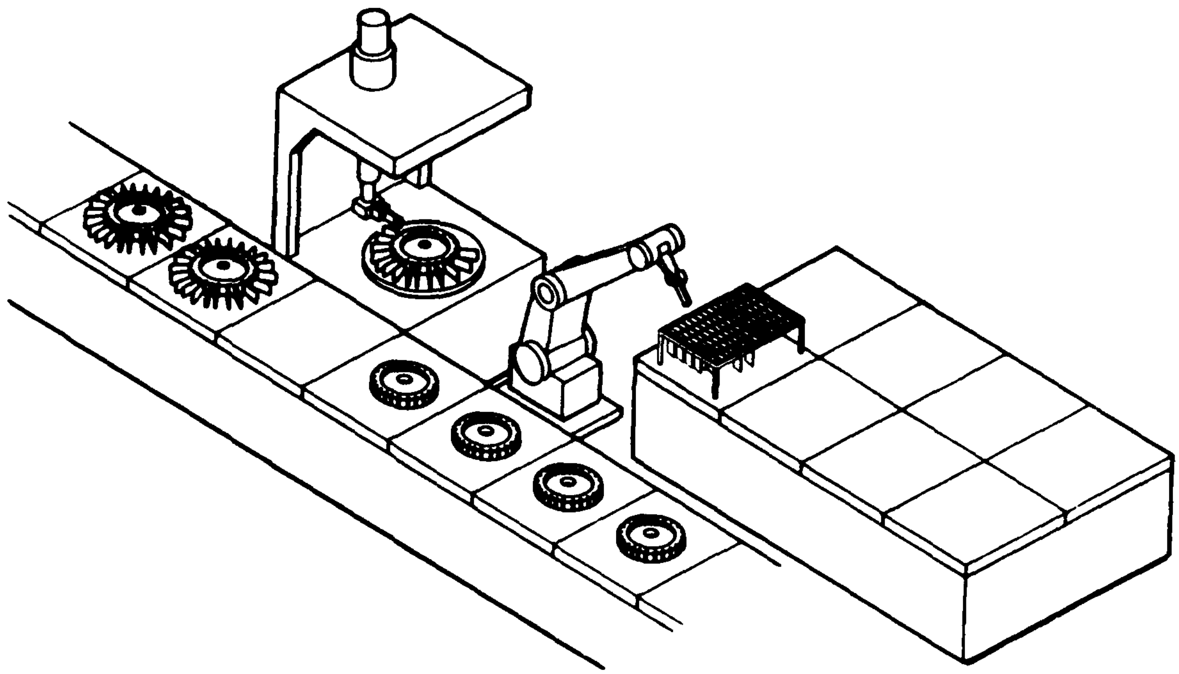

FIGURE 2-22 J-79 ENGINE ASSEMBLY SYSTEM. This system is to blade all 17 stages of the J-79 compressor. The material handler takes the first disk and set of blades from each of the input queues and moves them to their work station positions. The robot gets the appropriate gripper for that stage and picks up a blade. The robot moves the blade to the lubricant system and has it apply a coating of grease. The robot then tries to insert the blade into the disk, monitoring the insertion for jamming. Once all the blades for the disk are inserted, the bladed disk is moved to the output queue, where it has its paperwork updated, and is removed from the queue. The blade fixture, now empty, is cycled out of the work station position and back into the output queue. The next stage in the input queue is then cycled into the work station position and the process is repeated.

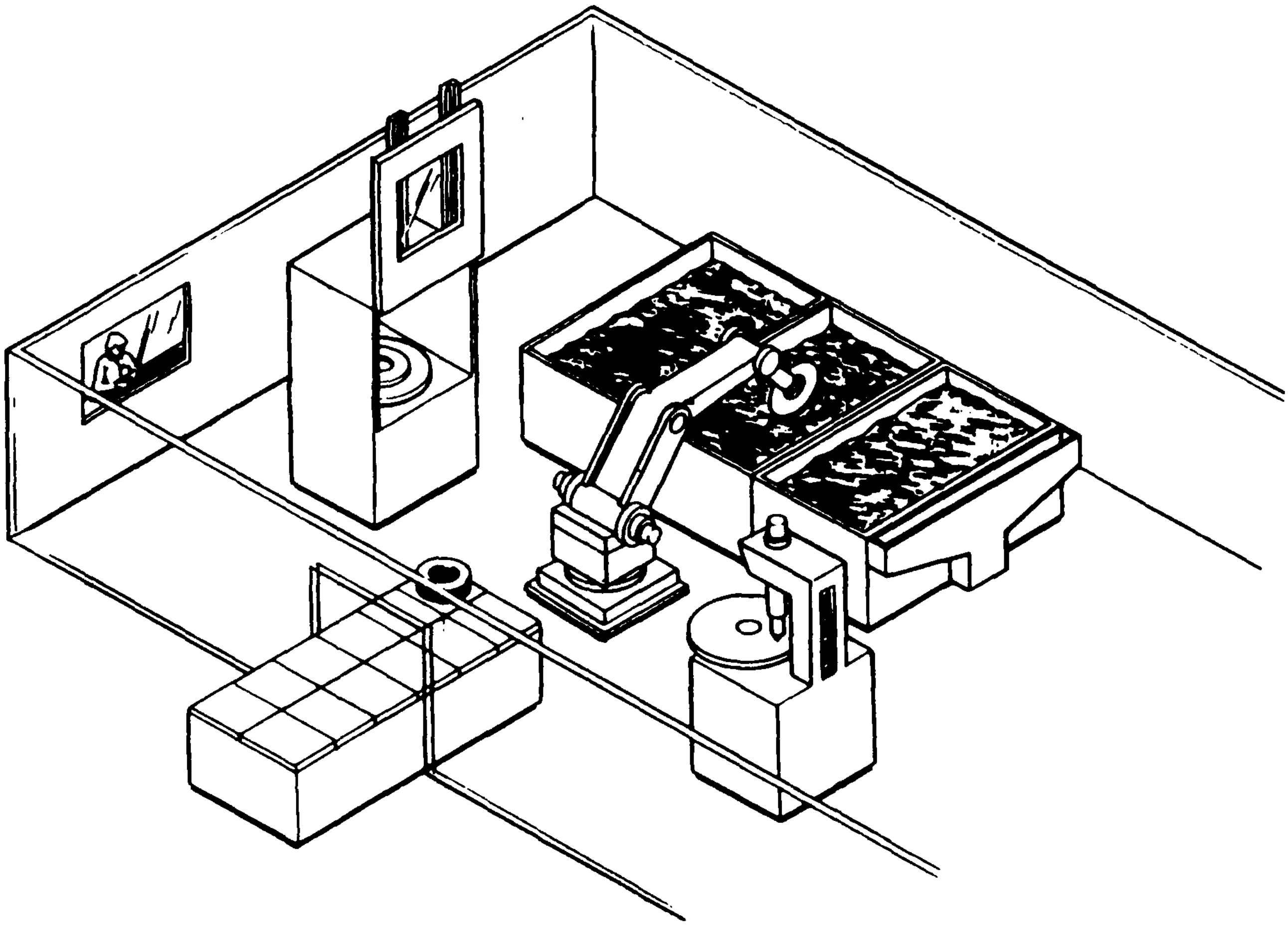

FIGURE 2-23 C-5 BRAKE DISASSEMBLY. The system removes brake pad and clips, then cleans the disks. This system greatly reduces the environmental hazard associated with handling beryllium parts. Also the processes in this application can be easily automated, so this application has low technical risk.

Technicians are still required to manually unpack the disks, clean the reusable boxes, and load the disks into the material handling system. The material handling system takes the disk from the unloading room and transfers it to the robot in another environmentally controlled room. The robot then mounts the disk on a three-axis turntable interfaced to the punch press. The turntable indexes the disk, as the punch press removes the rivets from the brake pads. The robot then removes the clips and pads from the disk. Once the pads are removed the disk can be cleaned.

that the component requires. The mature CAD/CAM data bases now available on many aircraft components provide an excellent incentive to develop a Multi-Function Fabrication Robot (MFFR). The MFFR is a machining center without fixtures that would do machining, grinding, drilling, routing, trimming, assembly, and inspection.

An operational high precision MFFR would eliminate the need for retooling, jigs, and patterns associated with today's manufacturing processes. Identical parts and components would be manufactured from the data base alone on any MFFR facility in the world. The four to one surge capability of such systems is of particular importance. The benefits are potentially very great.

2.5 Material Handling

Material handling for the Air Force has many robotic application opportunities, both at operational locations and at AFLC depots. These include supply, packaging, and transportation.

Supply

Supply activities at operational bases and AFLC depots have many opportunities for robot application. The Air Force standard base supply processing appears well structured for handling the peacetime level of activity at a fixed location. Assistance in the processing capability by portable robot aids should give an added capability for wartime levels of cargo activity at remote locations around the world.

Material handling in the field involves primarily the supplying of fuel and ammunition. Distribution facilities at logistics centers are also subject to the benefits of robotic automation.

The Army has an active robotics program for ammunition handling because they have to move large quantities of fuel, munitions, and supplies during wartime. The Army program is developing robots to handle pallets of ammunition and does not have direct application for the Air Force because of differences in the ammunition. The Air Force may wish to use robots for the logistics centers or develop specialized robot systems for loading airplanes.

The Air Force inventory system, larger than any commercial inventory, includes storage areas at every base, and major warehouse storage complexes at the five ALCs and specially designated ports for overseas shipments. Much of the storage and retrieval is manual. An inventory to support a wartime or contingency operation is required. Out-of-production parts are acquired and stored for the life of the systems using the parts. The small pieces necessary to do the major maintenance on larger items are acquired and stored and parts are also stored as they are returned for major maintenance.

Many storage and retrieval functions can be facilitated through robots and automation aids, saving manpower and providing a wartime capability of supporting around the clock operations. Commercial systems on a smaller scale are in use.

A base level system could be applied to over 100 bases, which multiplies the return on the investment of any variable system that is devised.

Packaging

The state-of-the-art of packaging technology should be exploited by the Air Force. Because each ALC appears to have different methods for packaging, a uniform automated system should be thoroughly explored. Systems are avail-

able that will cut and fold boxes to specified sizes. Integrating this automated boxing function with an automated "form-pack" system would eliminate most of the customized packaging now used. The packaging specifications should be integrated into the work instructions for packaging, storing, and shipping.

The Air Force maintains a record of standard packaging for each stock number of component in use. Most packaging crates and boxes are reusable. When a component is returned to the depot for major maintenance, it is unpacked following standard procedures. After repair, it is repackaged in a standard packing procedure. Some of the packing requires packing foam. The packaging operation requiring foam-in-place has been declared a hazardous or toxic operation by the EPA. It is also an operation where the quality of the pack and obtaining the correct amount of foam is strictly a function of operator skill and capability.

In wartime, the number of components requiring packaging will increase dramatically but skilled operators will not be available to meet surge levels. While these are highly repetitive and lower skilled operations, as the volume of activity increases, some recruiting and training of new personnel will be required.

Robots could do many of the repetitive tasks associated with the unpackaging and repackaging of components as they progress through the depots. This would reduce the labor intensity of the operation; speed the process; in the case of the foaming operation, remove the operator from a hazardous envrironment; and provide a surge capability. (See **Figures 2-24 to 2-27**.)

Transportation

The Air Force aerial ports have good processing capability with considerable mechanized materials handling equipment. Improvements in the processing capability of cargo through dispatch points would give added capability during periods of hostility. The need for personnel to visually read the labels of each parcel and then manually punch the numbers into a recording device is time-consuming when compared to a bar code reader. It should not be difficult to develop a hand-held bar code reader that would read the stock number, weight, volume, and destination of the package. (**Figure 2-28**.) In a similar fashion, the preparation of pallets for delivery to specific destinations should be improved through computer algorithms. All cargo requiring transit would be evaluated and automatically moved to the correct pallet for its destination. The proper build configuration, based on weight and volume, would also be computed at the same time.

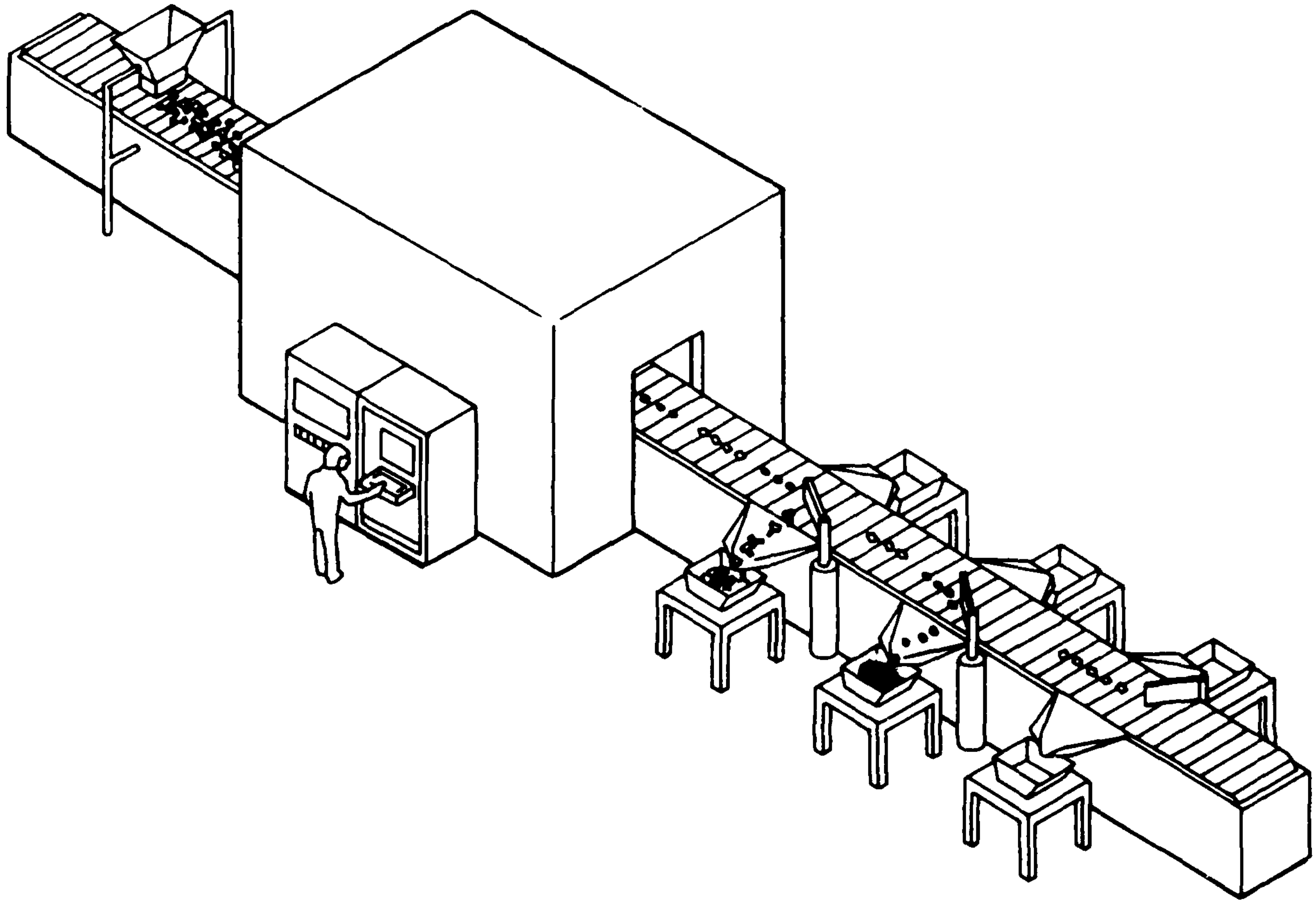

FIGURE 2-24 AUTOMATED PARTS SORTING. The first system to be developed should sort parts as they come from the plating area. This establishes a reasonable set size and provides the system with parts that are clean and consistent. Sorting techniques could be based on shape, size, weight and a variety of optical techniques. The exact use of these techniques will depend on the parts being sorted. Bowl feeders, screens, magnets, low-cost image systems, vibrators, and other similar devices are already used in industry for similar jobs.

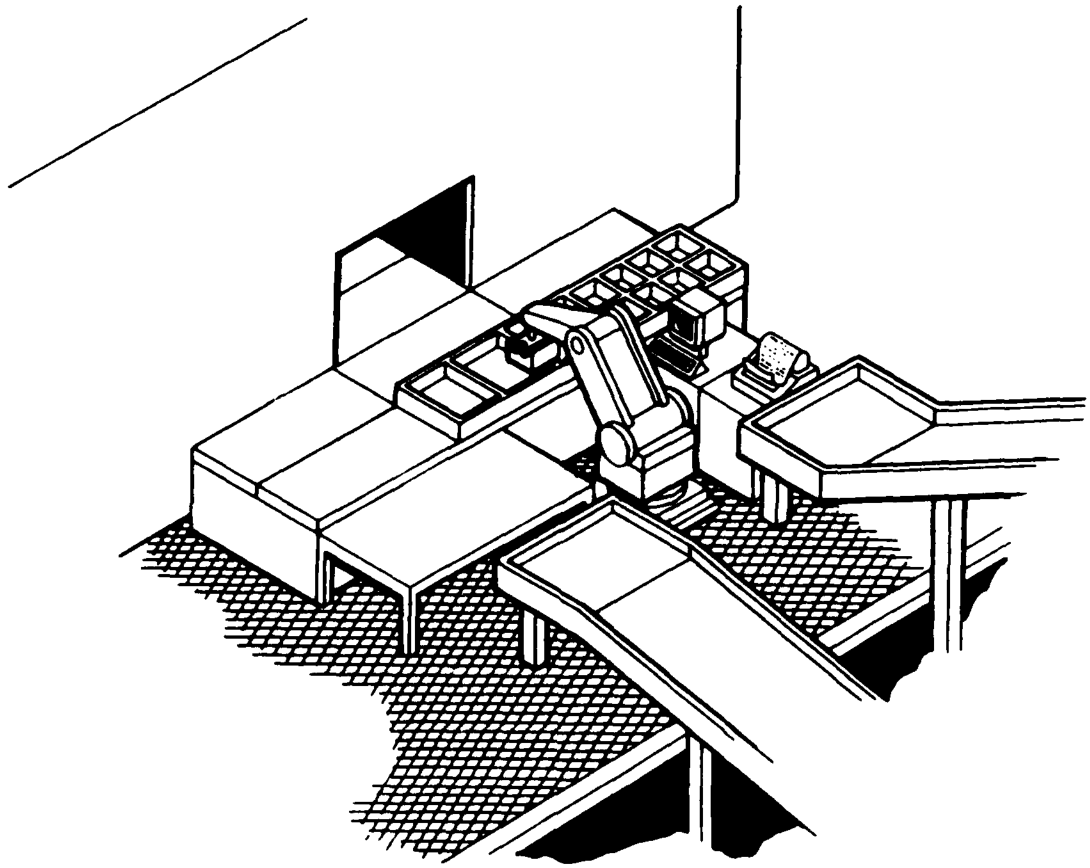

FIGURE 2-25 AUTOMATIC STORAGE MODULE. Until all boxes are bar coded with a standard format, quality bar code label, the prospects for any robotic system in this area is small. If all boxes were labeled with bar codes, at least three robotic systems could be installed on the ASM. The above system is not now available as an off-the-shelf unit, but most of the technology needed for this system has been developed and needs to be integrated into one system.

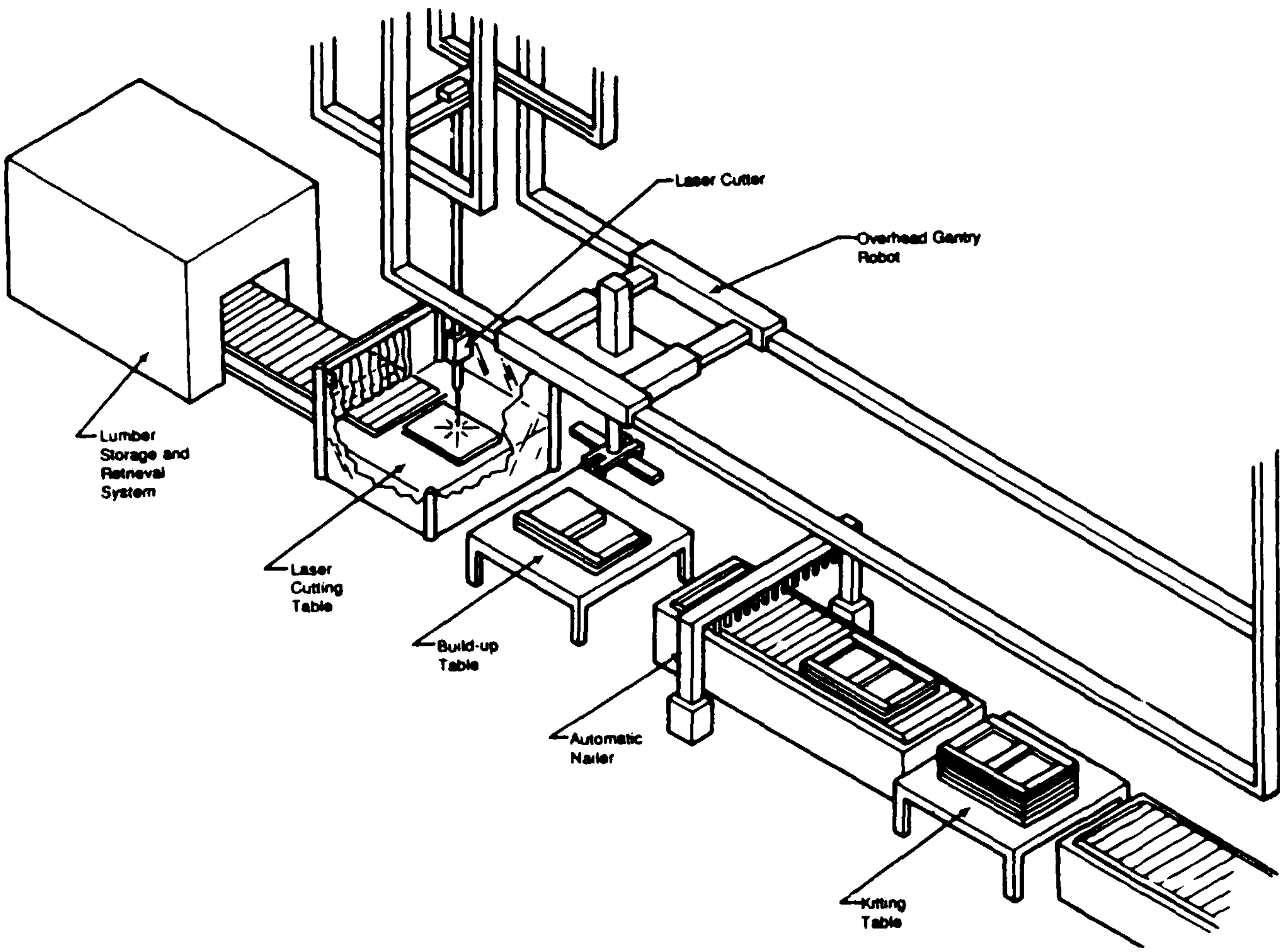

FIGURE 2-26 WOODEN BOX FACTORY. The order is entered into a computer system by either the dimension or the SPI number. The computer system then either retrieves or computes the cut list for the order. This cut list is then scheduled into the backlog of orders in the system. Optimization programs can be included to maximize material usage and minimize scrap.

The various cut orders are down-loaded to the cutting machines. Water jets, laser or conventional saws are used to cut the pieces. Lumber is retrieved from the storage system and cut. The remaining pieces are scrapped or sent back to the storage and retrieval system. The primary piece, required by the cut order, proceeds to a pick-and-place fixture for the assembly operation.

The assembly robot picks up the pieces and lays them out for nailing. A small spot of contact cement may be needed to hold the piece in place during nailing. The assembly proceeds to an automatic nailing/clinching station.

Once the nailing is complete, the sides are stacked and bundled for shipment to the requesting department. Each box must be stenciled according to the SPI. This can be done automatically using an ink-jet printing mechanism or a laser-etching operation.

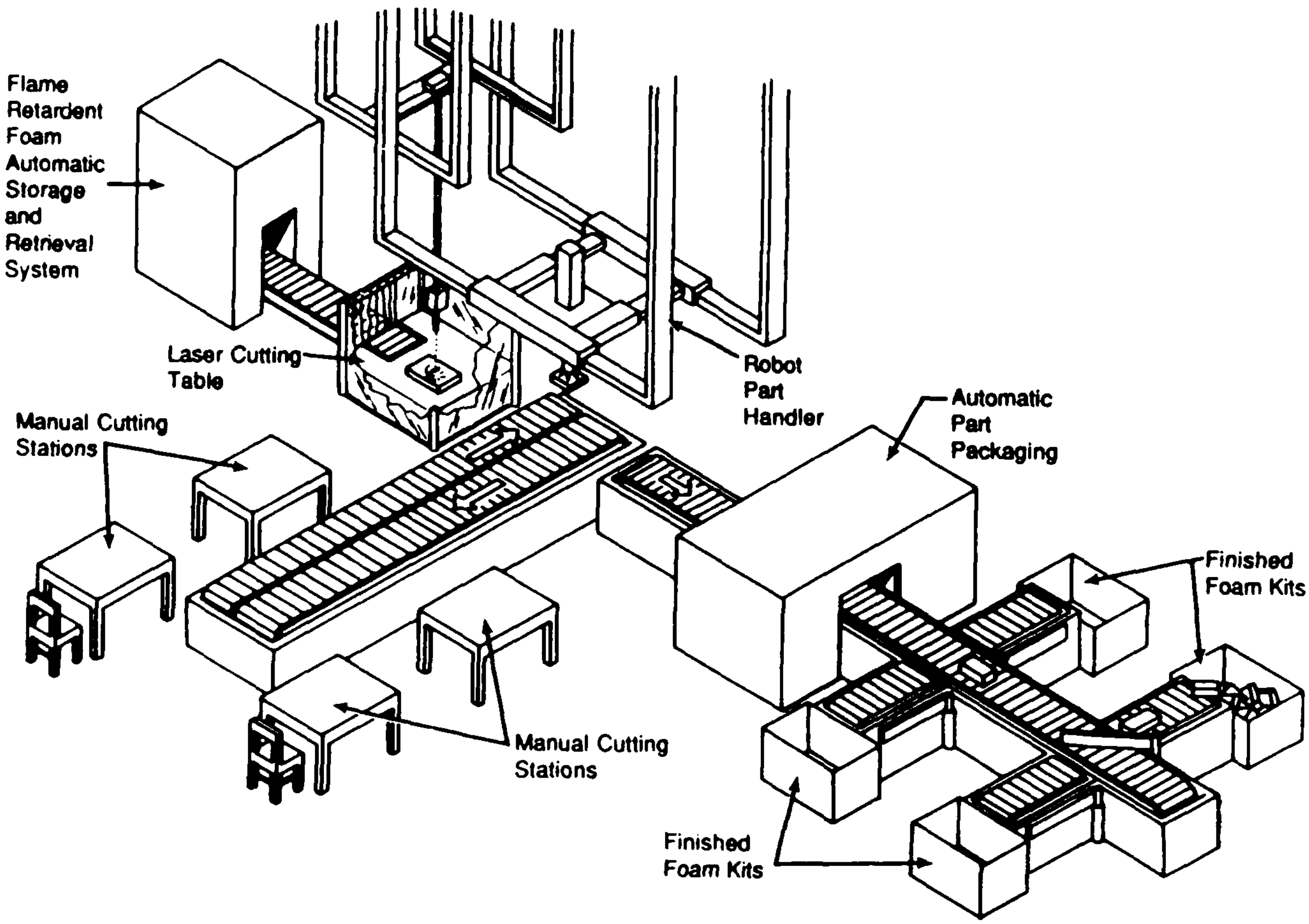

FIGURE 2-27 AUTOMATED FOAM CUTTING SYSTEM. The system hardware includes a foam storage and delivery system, material handling equipment, cutting equipment (laser and/or water jet and rotating knife), robotic manipulators, and marking and packaging equipment.

The control system contains a complete set of drawings for each aircraft kit in digitized form. The controller is programmed to control the entire sequence and includes optimization routines to ensure that cuts are made in a manner that minimizes scrap.

In use the system receives instructions to prepare certain parts or a complete kit. The appropriate foam stock is selected from the storage area and moved to the cutting area where controller routines compute minimum scrap layout for the parts to be cut from the stock. Parts are cut using the most appropriate tool for the application. If a hot technique such as laser or hot wire is used, the toxic fumes are collected and disposed of properly, therefore eliminating any operator hazard. The part is removed from the cutting area and moved to the marking station. For parts with unusual contours or milled surfaces, an intermediate station where final cuts are made by human operators may be required. At the marking station the part number from the drawing is marked on the part. It then moves on to the packaging station where it is wrapped, sealed, and labeled. The part is then ready for shipment or issue as appropriate.

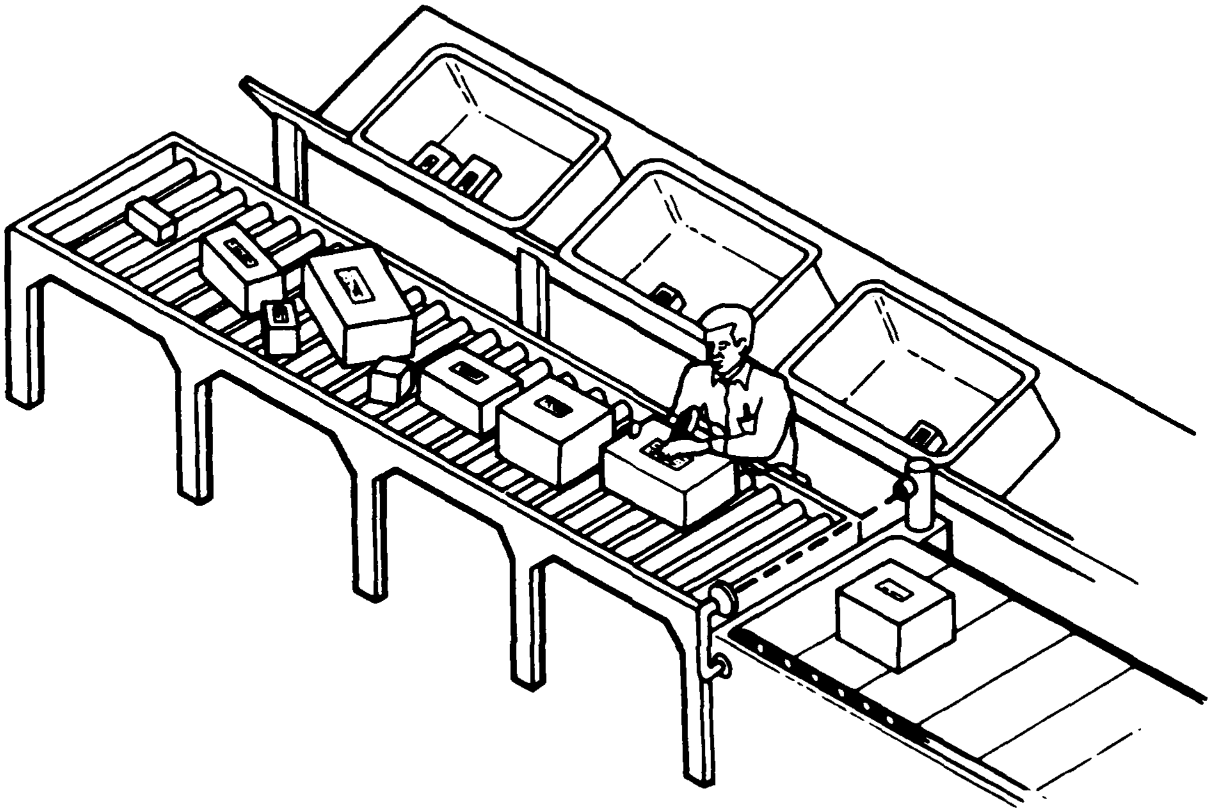

FIGURE 2-28 BAR CODE SORTER/POSTER. Items arrive as usual and proceed to the first station. The operator scans the bar-code strip on the shipping label. The package is then pushed onto the conveyor and, upon receiving the bar-code data, is automatically routed to the proper spur. The second operation and operator will be eliminated since the first operator is performing the combined functions.

Once the information is captured by the system, it can be retained and used to establish a tracking system. The location of all items can be identified in real time. Time stamps can be included so that expediting of items of a "greater than" age can occur.

3.0 RECOMMENDED APPLICATIONS

3.1 Introduction

Not all of the robot technologies reviewed in Section 2.0 are readily applicable or equally beneficial. To place the various applications in perspective, we developed selection criteria to evaluate each one. Using these criteria, we reviewed each application and selected for further R&D only those with the greatest potential benefit. The suggested R&D areas are discussed in Section 4.0.

3.2 Selection Criteria

As a first step in the selection process, we categorized the use of robotics into five major areas of application:

- Where there is an increased danger to humans as in the handling of hazardous materials, in chemical/-biological/radioactive (CBR) environments and in combat conditions;

- Where manpower has proved to be a major element, either as a result of a lack of trained personnel or where many people are required, such as in maintenance tasks or kitchen, hospital, and clerical tasks;

- Where cost containment is a major concern as in manufacturing and maintenance tasks;

- Where effectiveness of the combat forces and their enhancement is important, such as in air base and storage depot sentry duty, combat situations, and aircraft, satellite and missile applications; and

- Where there are space-based labor requirements for operations, construction, maintenance and repair of platforms, space stations and satellites.

Because the Air Force is primarily an operator of aircraft, is heavily involved in the space-based initiative, and uses various weapons to carry out its mission, we focused on how robots can best be used with these major systems. We identified the following specific areas of application:

- Servicing and maintaining aircraft
- Loading aircraft munitions
- Protecting and maintaining Air Force bases and storage facilities
- Runway Construction and Repair
- Personnel Decontamination
- Logistics
- Space Logistics - servicing and maintaining satellites and other space platforms
- Flexible Remanufacturing
- Education and training in the operation of systems and subsystems.

In addition to the above, we also looked at the probability of success of the technology and the impact of other technology-related areas such as:

- Availability of underlying technologies
- Time scale required for implementation
- Integration risk
- Confidence of achieving satisfactory implementation
- The "need" in terms of multiple applications

In the next step we applied all of these criteria against the importance of

the particular application to the Air Force. Some of the areas we looked at in this evaluation included:

- Importance of the mission
- Consistency with Air Force strategic planning
- Alternatives and availability of a back-up capability
- Environmental impacts
- Wartime versus peacetime scenarios
- Supportability within the current Air Force organization
- Importance of the mission to the Air Force
- Health and safety issues
- Overall economic impact on the Air Force budget

The committee found many of these parameters difficult to quantify and tried to derive a more qualitative system of measurement. We evaluated each criterion described above and selected the areas that seemed most promising. We then created a matrix and reduced the previously developed criteria to seven major areas:

- The degree to which the application involves exposing personnel to a hazardous environment,
- The degree to which robotics will allow manpower requirements to be reduced,
- The overall cost/benefit ratio for the application,
- Effectiveness of robotics in meeting the requirements of the application,
- Probability of success for the technology aspects of the application,
- Probability of success in carrying out the mission with robot technology,
- Importance to the Air Force relative to the other services.

These criteria were ultimately applied to the complete list of applications in order to focus on those areas deemed to hold the greatest potential for robotics and from which our recommended robotic applications were drawn.

3.3 Recommended Applications

Our recommended applications fall into three categories; (1) Applications that have a common basis with commercial robotic applications, (2) Air Force-specific applications that require adaptation of current technologies and limited research to meet specific Air Force needs, and (3) Air Force specific applications which require significant additional research in various technologies before development can begin.

We believe that action can and should begin immediately in each area. With regard to the first category, application of commercial robotics, action should include utilization of developed robots to meet Air Force functional requirements. For the second category, applying near term technology to specific requirements, development efforts should use off the shelf technology. This technology is available from current or near-term research and could be applied to specific Air Force requirements. For the third category, specific applications where additional research is required, research efforts should begin immediately if the applications are to be achieved in a reasonable time frame. Our recommended applications are summarized in **Table 3-A**. Section 2.0 contains detailed discussion of these applications.

Direct Application of Commercial Robotics

Many of the proposed robotic applications have a common basis in the commercial world. Practically all of these involve depot maintenance and resupply functions. For these classes of applications, the Air Force should concentrate on transitioning the technology

	Air Force Specific	
Commercial Application	**Short Term**	**Long Term**
Depot Maintenance	Aircraft Servicing	Flexible Remanufacturing
Distribution (Supply and Transportation)	Munitions Assembly and Handling	Space Logistics
	Air Base Security	Logistics Infrastructure
	Personnel Decontamination	
	Rapid Runway Repair	

TABLE 3-A

RECOMMENDED APPLICATIONS

from the commercial world to meet Air Force needs. This effort may require adapting the technology to respond to unique Air Force functional requirements. Limited research should be required for this category of recommended applications. Any research that is required should advance the common basis between commercial and Air Force related robotic applications.

The Honeywell study of Air Force depots concentrated on near term efforts. We believe the Air Force should begin a major project of comparable magnitude to define the technologies required to build the programmable, flexible manufacturing and remanufacturing centers for the Air Force of the future.

Air Force Specific Requirements

Many Air Force requirements for robotics are significantly different from commercial applications. This difference is a result of the functions performed, the location of the functions require mobility for the logistics support base (including the robots), or the nature of military matters that require peacetime preparedness while maintaining a combat capability. Functions not found in the commercial world include such items as the assembly and loading of weapons and the resupply of expendables in space. The possibility of a "come as you are" war requires rapid mobility of functions supporting aircraft operations. This support would include such normal functions as maintenance and servicing of aircraft, the deployment of which does not have a commercial equivalent. The combined peace-war function, striving for peacetime economy and wartime capability, does not have a commercial equivalent. Wartime flying operations may increase several hundred percent. The logistics support base must meet this "surge" with significantly increased logistics support in the form of maintenance and supply capability. A requirement to maintain the capability to multiply productive efforts several hundred percent does not have a commercial equivalent either.

Air Force Specific Requirements - Short Term. This class of recommendations focuses on near-term, high payoff functions that could be developed to meet specific Air Force needs with limited research. The development of these functions would likely be an adaptation of research to Air Force specific problems in the areas of aircraft servicing, munitions assembly and handling, air base security, personnel decontamination, and rapid runway repair. With respect to the latter application, the Air Force engineers should begin a joint program with the Army and monitor and apply appropriate commercial developments to their unique military needs. At a minimum, the adaptation of existing research must be developed into a practical solution. Adaptive research and creative development will be required because there is no known commercial basis for direct application.

The term, "short-term application," implies that there is some form of near-term solution. This does not mean that better solutions will not come from additional research. This class of near-term solutions should probably be considered as the first phase of solutions, with new and better solutions to follow. These applications will in reality be the first generation of the application of robotics to respond to Air Force needs. Certainly follow-on generations of robotics and automation will clearly produce better solutions to these problems. Considerably more research will be required before the next generation will be ready with improved solutions.

The specific Air Force needs and potential applications discussed in Sec-

tion 2.0, which did not have a common basis with the commercial world, were evaluated using the criteria from Section 3.2. Some applications formed natural groups for technology application as well as Air Force needs. These natural groups were then reviewed for their importance to the Air Force in both peace and war. The groups in turn formed clusters, some of which were deemed important in both peace and war, while others that were relatively unimportant in peace could be useful in war. This latter category displayed the credentials of being important if required, but included a conditional probability as their true requirement is unknown. Examples of this would be personnel decontamination following a chemical or biological attack and rapid runway repair following attack. Each is extremely vital after the attack, but the severity must be balanced by the probability of attack. These classes of requirements fall somewhere below the requirements that are known to exist regardless of the attack scenario, and which are also important in peacetime. The five groups are listed below; the first three are very important in peace as well as war. **Table 3-B** depicts specific short term Air Force applications as subjectively and relatively weighted on a scale of 1, least important, to 10, most important, in a war and peace matrix.

Applications 1 through 3 are vitally important in wartime -- an indicator of where to concentrate budget priorities.

Applications 4 and 5 are of minimal concern in peacetime, but in war become important, depending on the scenario and whether the bases are attacked.

Air Force Specific Requirements - Long Term. Air Force specific requirements for the long term are considered to be major Air Force requirements for robotic applications that do not have a commercial basis and that also do not have any known near-term solutions from limited research and development. Future robotic applications must encompass changing political climates, systems with new technologies, changing demographics, and revised national priorities. This class of applications will require basic research or, as a minimum, long periods of applied research before success is achieved. These areas: flexible remanufacturing, logistics infrastructure, and space logistics, probably have the highest potential for payback or return on investment. However, due to the length and uncertainty of the research required, they are less specific and have more generalities than the prior classes of needs and applications, and therefore have not been incorporated in **Table 3-B**.

For space applications, we believe that the Air Force should immediately increase the research required for a balanced space robotics program. The Air Force should expand their efforts and pursue the necessary R&D in cooperation with other government agencies such as NASA, the Defense Advanced Research Projects Agency (DARPA), and the Strategic Defense Initiative Organization (SDIO). In particular, the Air Force should establish a concurrent development effort with NASA in space-based robotic efforts to complement NASA's efforts. The Air Force R&D effort should include pursuing development of lightweight robot structures, multiple arm dexterity, vision, sensing, and robot modularity (so robots can repair themselves and continue to work). Supporting software will require on-line prioritization of many operational criteria with nominal intervention from distant human operators supervising from the space station or from the ground.

	Application	Peace	War
1.	Aircraft Servicing	8*	10
2.	Munitions Handling	4	10
3.	Airbase Security	9	9
4.	Personnel Decontamination	1	5
5.	Runway Repair	5	7/10 (Scenario Dependent)

TABLE 3-B

SHORT-TERM SPECIFIC APPLICATIONS (Relative Importance)

* 1 = least important

10 = most important

4.0 ENABLING TECHNOLOGIES: NEEDS FOR RESEARCH AND DEVELOPMENT

We have identified potential applications of robots to fulfill Air Force requirements (Section 2.0) and proposed recommended applications for Air Force consideration (Section 3.0). In this section, we relate the robot technologies to our candidate applications to determine the research required in each application area.

Table 4-A presents our measure of robot technology requirements against our recommended candidate applications. This table lists each recommended Air Force-specific application across the top. Each of the principal technologies involved in robotics and its subcomponent technologies are listed on the vertical axis. An entry in a particular row and column deals with the applicable component robotic technology needed for a specific Air Force robotic application. This table is appropriate *only* to those Air Force applications defined in this report. Naturally, additional candidate Air Force applications will be developed by the Air Force as it progresses in developing and applying technology in this field. Air Force personnel planning these new applications should be aware of the spectrum of R&D needs across robot technologies, so that if new applications require different uses of technologies, they will be in a position to structure the required research. (NOTE: For an in-depth overview of the state of robot technologies, see Appendix A.)

Our recommendations for technology research are presented below under each of the four major topic areas and their associated component technologies. These recommendations identify the leading research issues in each area.

4.1 Computer Control System

In this area the committee recommends that the Air Force:

- Develop formal models for hierarchical control systems.
- Conduct research and development activities on the use of next generation intelligent software technologies for robotic systems.
- Investigate the use of distributed parallel supercomputer architectures for robotics.

4.1.1 Hierarchical Control Systems

- While many researchers have used the National Institute of Standards and Technology real-time control system (RCS) as a model for the development of robot controllers, the lack of a formal mathematical model for the RCS is considered an impediment to more rapid progress. The formal mathematical model would define the relationships between levels, the multiple points of view, and the interaction between both the control action side and the sensory side of the control system with the world model. It would address the subdivision of control levels into planning and execution models, and define methods of coordination and cooperation between multiple events at the same level. These formalizations will reduce the creation time for the development of multi-layered control systems for sophisticated robot systems. For these reasons, the Defense Advanced Research Projects Agency (DARPA) has begun funding in this area.

- The development of a real-time debugging environment has been a problem in the development and testing of sophisticated RCS implementations. New ways are needed in this area to replicate errors and monitor in slower than real time what takes place in the RCS. Various graphical interfaces, data capturing schemes, and development tools are being researched, but a breakthrough is needed, and will require more significant levels of funding to achieve.

- The maintenance and development of an RCS for a particular application area remains a significant task without the use of many formal tools. (See also the discussion on Human Interface System in Section 4.4.) The development of application specification tools would drastically increase the productivity of the teams building RCS applications.

4.1.2 Machine Intelligence

4.1.2.1 Reasoning/Inference

- Knowledge representation is perhaps the most significant topic for research in this area. While many are working this issue and many schemes are being investigated, the area remains seriously in need of significant advances.

- As the application areas grow the intersection with machine intelligence and knowledge representation crosses into the arena of data bases and all the related issues of distributed data base systems. Integration across independent systems and redundancy equivalence.

- The problems of conflicting data, partial data, and resolution of multiple representations of data and equivalences will require significant advancement for general applicability. This advancement is important for developing the capabilities of machine intelligence.

- While the speed of computers continues to increase dramatically every year, the searching required by machine intelligence algorithms remains a challenge for the fastest computers. Much research is on going in the area of reducing search time by using information and clever arrangements within the representation scheme. Until either the speed increases by several orders of magnitude or research bears a significant result, search time must continue to be an impediment to the size of problems attacked by machine intelligence.

- The passing from von Neumann computers to the next generation systems (parallel machines) promises to be both an asset and deficit to machine intelligence. On the one hand, the organization of a hierarchy of levels lends itself nicely to parallelism; we do not yet know how to break up an inherently non-parallel subtask to run efficiently on a parallel machine. Research in this area is motivated both by the need for speed and the expected successful commercialization at affordable prices of parallel computation systems.

- The enhancement of planning and executor modules in machine control systems must be the focus of significant research. At present these capabilities are only rudimentary in terms of repairing and abandoning plans as well as the formulation of plans with alternatives.

4.1.2.2 Sensory Perception

- The definition of an interface for

ROBOTIC TECHNOLOGIES AND SUBCOMPONENTS	RECOMMENDED ROBOTIC APPLICATIONS: Short Term					Long Term		
	Aircraft Servicing	Munitions Handling	Air Base Security	Personnel Decontam.	Runway Repair	Flexible Remanufac	Logistics Infrastruc.	Space Logistics
Minimum Time to Implementation (Years)	3	4	5	5	5+	5+	10	10+
4.1 Computer Control System								
4. 1.1 Hierarchical Control Systems	d	D	D	D	D	R	R	R
4.1.2.1 Reasoning/Inference	r	d	r	d	D	d	r	R
4.1.2.2 Sensory Perception	d	d	D	d	D	r	r	R
4.1.3.1 Object Oriented Systems	d	d	D	d	D	d	r	R
4.1.3.2 Intelligent Data Systems	D	d	d	d	d	r	r	R
4.1.3.3 Software	d	d	D	d	D	r	r	R
4.1.4 Computer Architecture	m	m	m	m	d	r	r	R
4.1.5 Sophisticated Communications	m	m	M	m	M	d	D	r
4.2 Sensor System								
4.2.1 Force and Positional Sensing	M	d	m	d	m	D	d	D
4.2.2 Imaging Sensors	d	d	m	d	m	d	D	r
4.2.3 Image & Speech Understanding Systems	d	d	D	d	D	r	r	R
4.2.4 Other Sensors	m	m	d	d	d	d	d	D
4.3 Actuation Systems								
4.3.1 Structural Geometry	M	D	m	d	d	r	D	r
4.3.2 Structural Dynamics	d	r	M	M	d	R	D	R
4.3.3 Actuation Mechanisms	d	D	d	d	D	R	r	R
4.3.4 Manipulator Systems	D	D	m	M	d	r	r	R
4.3.5 Internal Decision Making & Control	r	r	m	d	d	r	r	R
4.3.6 Mobility and Portability	D	D	D	d	D	r	r	r
4.3.7 End-Effectors	d	D	m	d	d	r	r	r
4.4 Human Interface Systems								
4.4.1 Operating Requirements								
4.4.1.1 Universal Controller and	d	r	d	d	d	D	D	R
Operational Software	d	r	d	d	d	D	r	R
4.4.2 Teleoperation	d	D	M	d	d	d	D	D

Legend

- m = Robotic technology required is available with minor modification
- M = Robotic technology required is available with major modification
- d = Some development in robotic technology will be required for Air Force application
- D = Extensive development in robotic technology will be required for Air Force application
- r = Some research required in robotic technology for Air Force application
- R = Extensive research required in robotic technology for Air Force application

TABLE 4-A

RELATIONAL INDEX FOR ROBOTICS TECHNOLOGIES

AND CANDIDATE AIR FORCE-SPECIFIC ROBOTIC APPLICATIONS

communication of requirements and results would greatly improve the ability to develop the sensory system independently of the control system.

- The need for multiple points of view in the world model must be supported by the sensory system.

- The problem of avoiding a self-fulfilling prophecy is difficult when the fit is bad. When looking for a target, all things tend to resemble that target if one is not careful.

- The development of a reverse hierarchy for sensory information processing that has multiple levels, and spans of interest (such as the control system) is under way. However, this reverse hierarchy needs as strong a focus as that on the control side. Such research has not been actively conducted and is needed.

- The ability to easily add and remove single and groups of sensors and sensory types from a hierarchy with graceful degradation or enhancement is also an important research area.

4.1.3 Software Systems

4.1.3.1 Object Oriented Systems

- Increased efforts are required in defining object oriented systems. What is needed is to use the current momentum and increase the pace of development and applicability to robotic systems.

- Significant focus must be applied to the integration of modules in heterogeneous computers and development in uncoordinated efforts.

- A better understanding must be achieved regarding the impact of distributed computing, networks, and dynamic structures on the requirements and specifications for object oriented systems.

4.1.3.2 Intelligent Data Systems

- Efforts need to be focused on defining specifications for robotic world models.

- Increase the scope of effort in tying the information retrieval community to the AI community. Robotics is dependent on mutual efforts of these two communities which have only just begun to work together.

- This research should be linked seriously and carefully to the object oriented approaches described above.

- Focus the needs of this work as a test bed for the new developments in parallel computing architectures. This research will be used as a vehicle for the implementation of robotic control systems.

4.1.3.3 Software Environment

- The environmental issues for robotic systems are in some sense the most well defined and the smallest of the massively parallel architectural challenges being looked at by this community. A focused set of requirements and source of funding would coalesce this research. Together they would significantly shorten the amount of time needed for use in the development of military robotic control systems.

- This topic is highly interdisciplinary even within the computer science arena. Interactions of normally diverse communities of researchers will again speed up the development of appropriate systems for this research.

- Work on the software issues described above relates not only to all the software research issues identified in this section, but is highly linked to the hardware architecture developments as well. It should not be significantly decoupled. The pace of new developments has literally integrated the hardware and software fields at the architecture level. Any attempt to seriously separate them will impact or impede progress.

- With respect to software reliability, robotic systems will pose a new level of danger from faulty software. That is, they can now fail in an active mode and cause harm. In the past, failures either gave wrong information or failed to initiate action. Thus, the stakes are high and research should be pursued. There are no easy or quick payoff research areas that can be identified at this time.

4.1.4 Computer Architecture

- Increase focus on robotic applications, for example, new control and computer architectures suitable for robots with many degrees of freedom and great dexterity. These are good tasks for the parallel computing systems research community, who are looking for real applications.

- Take advantage of the developing state-of-the-art systems to design and produce custom chips, to design chips for generic robotic applications. Many actuator functions, simple sensor transducers, or floating point hardware to allow for real-time solution of robot dynamical equations are obvious first candidates.

- Examine the potential impact on progress in robotics if a tight linkage to chip designers is forged. In particular, consider the speed advantage in single chip architecture possible in gallium arsenide chips.

- Develop standards for interconnection of multiple processors and communication systems able to meet the requirements for robotic systems.

4.1.5 Sophisticated Communications

- Actively focus on the need for a standard that will not impede the development of new technology, but permit multiple systems developed independently to easily be interconnected. These standards for robotic use must include the time dimension in terms of transmission time as well as the logical interface of connected systems.

- Increase the number of computers that can be *tightly coupled on a bus* structure.

- Focus on the reliability of communication systems for robotic systems in hazardous environments and battlefield conditions.

- Develop a capability to instrument and schedule information in a communication system.

- Do the research and development necessary to develop a communications system that takes information criticality into account in its operation.

- Develop ways to gracefully degrade communications systems and recover from partial disruptions of the system.

- Investigate special communications modalities which allow for non-tethered robotic system operation. Examples could include special

frequency radio wave systems.

4.2 Sensor System

In this area we recommend that the Air Force undertake research to:

- Resolve conflicting sensor information.
- Improve the capabilities of all the various sensor types.
- Define a common set of sensor interface specifications.

4.2.1 Force and Positional Sensing

- Focus on the development of artificial skin with tactile or taction capability. While some work is ongoing in this area many advances are needed in terms of resolution, range of forces, accuracy, and compliance of the artificial skin to arbitrary surfaces. In addition, the adverse conditions for operation of these sensors present yet another challenge.
- Carry out appropriate research and development activities to increase the capability of force and torque sensors for robotic applications. Challenges exist in size, sensitivity, and mounting with respect to usefulness on a robot.
- Increase the sophistication levels of range finders and other sensor systems that although mounted or located external to the robot provide positional feedback for increased robotic accuracy.

4.2.2 Imaging Sensors

- The continued development of special purpose very large scale integrated (VLSI) chips for image processing at increased image sizes and speeds will be required for advanced robotic applications.
- Develop higher resolution and increased reliability image sensors across the various spectral possibilities, visible, and infrared.
- Continue generic low level image processing research to increase capability and speed of these systems.
- Continue progress toward an understanding of how to use knowledge in image processing applications more effectively and reliably.
- Develop better understanding in how to deal with the time domain. Handling multiple images acquired at varying points in time which require sophisticated hardware and software analysis for proper utilization.
- Improve the formulation of three dimensional data from multispectral and other special multiple image sources.

4.2.3 Image and Speech Understanding Systems

- Increased capability in less controlled environments are required for both image and speech understanding systems in advanced robotic systems. This area is considered too broad in scope for detailed analysis here.

4.2.4 Other Sensors

- Significant effort must be expanded on developing specifications for the integration and interconnection of modular sensors and sensor systems to robotic control systems.
- Standards for sensory system data,

mechanical electrical connection, as well as contextual information are required for rapid progress in retrofitting robotic control to existing systems.

- Generalized methods for adopting various sensors to robotic applications must be developed.

- A model for describing sensor semantics for inclusion with the perception hierarchy is required for proper sensor integration and rapid advances in building sensor systems with arbitrary collections of "other" sensors.

4.3 Actuation Systems

In this area we recommend that the Air Force:

- Develop multi-criteria control of modular lightweight serial and parallel architectures.

- Improve physical plant modeling in real-time software.

- Achieve adaptive control for process disturbance rejection.

4.3.1 Structural Geometry

- Study the architectural role of 1, 2, 3 degree-of-freedom (DOF) modules in dexterity and control issues.

- Study geometric criteria to develop decision-making algorithms for the operation of redundant (extra DOF) and multiple arm systems.

- Evaluate the comparative benefits of serial, parallel, and layered architectures to improve manipulator performance for a broad range of functions.

4.3.2 Structural Dynamics

- Develop a semi-autonomous technology to evaluate the actual parameters of a robot system (dimensions, deformation, mass, and control parameters).

- Develop computer-generated descriptions of robot architectures for efficient physical plants.

- Treat dynamic phenomena associated with docking, cherry picker configurations, or moving platform dynamics.

- Develop techniques for multiple arm operators that compensate for system deformations induced by operating disturbances.

4.3.3 Actuation Mechanisms

- Develop a full spectrum of actuators that may be compliant, stiff, light weight, energy efficient, extremely small, exhibit little stiction, without backlash, or low in reflected inertia, and have high resolution, linearity. Develop actuator modules that combine special rigid anti-friction bearings, lightweight materials in parallel structures for compactness containing 1, 2, 3, or more DOF.

- Develop a modular based robot architecture composed of a broad range of easily scaled and interfaced modules that can be assembled by rules in an expert system to meet the requirements of a given application

4.3.4 Manipulator Systems

- Develop architectural design procedures for manipulator systems that broaden their physical task spectrum.

- Develop combinations of materials and structural geometry for enhanced system stiffness and load capacity.

- Enhance the precision operation of manipulators by developing better components (anti-friction) and disturbance rejection control software.

- Study ways to enhance the reliability of robot systems in particular for field and space operations.

4.3.5 Internal Decision Making and Control

- Develop control technologies that make the robot system increasingly electronically rigid, massless, and with constant parameters.

- Develop control technology that makes process disturbance rejection feasible for enhanced precision tracking.

- Develop layered mechanical and software structures that best reject disturbances as may be found in light machining tasks.

- Develop adaptive control techniques that adjust the control system parameters in real time to best enhance performance.

- Develop a structured decision-making technology based on 25 or more operational criteria to operate in real time on realistically scaled system computer hardware.

- Develop requirements for a computer architecture and its associated software that best enhances a broader mechanical architecture.

4.3.6 Mobility and Portability

- Continued research into locomotion (legged) and multiple arm (fingers) operation is essential for field and space operations. Mobility on the space platform will require continued development.

- Portability implies improved development of navigation, world data bases, and sensory referencing of the mobile module.

4.3.7 End-Effectors

- End-effectors are the operating tools of intelligent systems. Hence, their development to meet specialized Air Force requirements is necessary.

4.4 Human Interface Systems

We recommend that the Air Force:

- Investigate balanced human and computer control.

- Conduct research into needs for human intervention at higher decision-making levels.

- Achieve stand-off operation of many remote robot units.

4.4.1 Universal Controller and Operational Controller Software

- Perform an in-depth assessment of operational requirements in the field and in space especially to account for unexpected events and emergencies such as forced outages and damage from space debris.

- Create a balanced technology that enhances both human and/or computer control of the proposed robotic technology.

- Develop improved control technology that improves autonomous capabilities of the robot and allows human intervention at higher supervisory levels of control.

4.4.2 Tele-operation

- Develop a level of machine intelligence that eliminates low level man-machine interaction and increases autonomous control capabilities.

- Develop the technology that allows human intervention at increasingly higher decision-making levels.

- Develop training systems to enhance performance of human operators.

5.0 CONSTRAINTS AND ISSUES

5.1 Robotics as a Representative and Reflective Element of Philosophy, Policy, and Attitude

So far we have concentrated on the opportunities for the application of robotics technology available to the Air Force. However, in the course of this study, we were provided with a "window" on underlying Air Force policy, philosophy, and attitude toward robotics. This section summarizes our observations and concerns about this broader aspect of our study.

Despite Air Force Systems Command (AFSC) support and the fact that logistics is approximately 40 percent of the Department of Defense (DoD) budget, logistics R&D, perhaps because of its lack of excitement, has a relatively low priority in DoD and in the Air Force, compared to projects such as stealth aircraft, composite materials, engine development, and in a broader DoD sense, C^3. Air Force logistics R&D programs are active but represent a weak technological base. As we have stated previously in this report, the prime area for the application of robotics is in logistics support. Thus, logistics R&D clearly needs a better focus, an individual or organization to be its advocate, a stronger technical base, and generally enhanced visibility and stature within the Air Force (and DoD in general).

While our reactive posture to a threat remains unmatched anywhere, Air Force logistics technology during peacetime suffers from neglect rather than by a failure of purpose. This puts the Air Force technologically at risk overall: a decade of reduced technological advancement can no longer be rectified by mounting a large reactive attempt in a short time period, as during a crisis.

It is necessary and timely that the Air Force face its role with respect to logistics and technology. The Air Force must develop and maintain a level of technology and application that would permit it to respond favorably to a surge requirement. A competitive, proactive approach is needed to direct the proper attention and priority to this issue.

Emerging logistics needs include parts on demand, resupply under attack, repair in the field, operations in a chemical/biological/radioactive (CBR) environment, increased depot automation, Strategic Defense Initiative (SDI) operations, and in the long term, a next-generation repair facility. These issues, particularly the last one, require a fundamental philosophical change in the Air Force that would embody design for automation and robotics. This concurrent engineering approach includes designing for automation, assembly, manufacturability, maintainability, and reliability.

Also central to meeting these emerging logistics needs are fundamental technological fields that should be addressed now so that we may properly respond to these application needs and the high levels of uncertainty inherent in them. Growth and development of electrical, mechanical, and systems engineering, and computer science and engineering must be fostered within the Air Force. We are investigating machines to augment the human process both in mind and muscle and, as such, naturally evolve to artificial intelligence

(AI) and robotics, respectively. We are heavily integrating electro-mechanical systems, using computers for decision making, and using data base driven machines. Robotics is rapidly transitioning to the area called intelligent machines, combining robotics and AI.

Robotics is not broadly pursued and accepted in the Air Force. In technology and applications, Air Force robotics lags significantly behind the industrial sector. Robotics is an exciting technology and a "hot button" field in different sectors of our society, yet this committee saw several Air Force robotics installations idled because personnel did not know how or were not motivated to use the equipment. Also, we noted a lack of integration of robotic and computer technology in obvious application areas and a lack of enthusiasm for upgrading into this technological field. There were of course, special areas such as non-destructive inspection (NDI), where we found unbridled enthusiasm on the part of many personnel.

The Air Force must change its policy, philosophy, and attitude toward the use of robots in logistics so that acceptance is gained quickly and applications are used effectively by a willing work force that recognizes the need and the impact in the short and long term. In the remainder of this section, we carefully review five areas of concern that require attention:

1. Organizational structure and prioritization

2. Technology transfer and exchange

3. Manpower and skill levels

4. Market, technological, and lifetime time constants

5. Design for automation and robotics

5.1.1 Organizational Structure and Prioritization

Though we have emphasized the need for prioritization in R&D, applications, organization, and personnel, this need is not restricted to the Air Force. In his April 26, 1988 address to the National Academy of Sciences, NAS President Frank Press said:

The issues are funding levels and priorities....The seemingly intractable problem of setting priorities in the allocation of R&D funds has dominated the discussions at our Academy's regional meetings and it consumes my correspondence and conversations with members....Part of the difficulty with the budget and appropriation process can be attributed to the disarray of the federal government's system for developing the science and technology budget. It is astounding but true that nowhere in the federal budget-making process is there an evaluation of the complete federal budget for science and technology and its overall rationale in terms of national goals.

5.1.2 Technology Transfer and Exchange

While resolving the national issue is beyond the purview of the Air Force, AFSC should more aggressively pursue robotics through an organization that can capitalize on robotics technology development in the other services, government agencies, academe, and industry. The Air Force can achieve significant savings in time and development costs of robotics by enhancing its ties with industry and academe and by greater cooperation and exchange of ideas with the other military services, as well as within the Air Force itself.

5.1.3 Manpower and Skill Levels

Manpower and skill levels must also be seriously considered. Extensive implementation of robotics will require people of higher skill and education than are generally available in the Air Force. At the same time, robotics will, if properly implemented, reduce the number of personnel required. These requirements will likely bring some changes in Air Force recruitment.

5.1.4 Market, Technological, and Lifetime Time Constants

There is an incompatibility between the time to market a product (or deploy a system), the fundamental technological time constant inherent in that system, component or product, and its natural lifetime. The DoD takes a long time to develop and deploy weapon systems. This constraint is of particular concern in the face of more rapidly changing technology yielding shorter and shorter technological time constants. As a result, the Air Force has aircraft and systems flying that are antiquated, with respect to the integrated technology it could utilize today, despite incremental and necessarily frequent upgrades.

The Air Force, as the service most dependent upon the continued and successful application of technology to support its mission, should take the lead in seeking ways to reform the acquisition process.

5.1.5 Design for Automation and Robotics

Design for automation and robotics is as important as human engineering design. Concurrent engineering and design objectives must also be implemented. Each of these points are now described in greater detail.

5.2 Organizational Structure - Need for a Focus

The Air Force has two types of commands: operational commands and support commands. The operating commands fulfill various basic missions of the Air Force, while the support commands perform essential support functions that enable the operating commands to perform their missions in peace and war. Support commands include the AFSC, which is responsible for the research, development, and acquisition of systems used by the operating commands, and the Air Force Logistics Command (AFLC), which provides logistics support for systems after they are developed and fielded. Separation of systems development and follow-on support differentiates the Air Force from the Army and Navy, where the same organization is responsible for a system throughout its life cycle. The Air Force system of separation of responsibility makes it more difficult to get feedback from the support areas into the design phase, which is the proper place to consider the application of robotics and automation in the design of new systems.

Perhaps because of this organizational structure, the Air Force has not developed a center of expertise for robotics as have the Army and Navy. It is not clear where in the Air Force the responsibility lies or who should take the lead in developing a center of robotics expertise to meet long and short term Air Force needs. As a consequence, neither the Systems Command nor the Logistics Command has developed a central organization to deal with the emergence of robotics technology.

The Air Force should establish a mechanism for initiating, developing, and producing a robotic based application. The largest Air Force research effort into robotics is run by the Air Force Materials Laboratory under the manufac-

turing technology (MANTECH) effort. However, MANTECH has been reduced to less than 50 percent of the original funding in the last few years. The major efforts to fulfill the robotic requirements of the AFLC depots are being conducted under the repair technology (REPTECH) program, considered to be a subset of MANTECH. This effort emphasizes that the robotic efforts of the depots are more closely aligned to a first level of implementation similar to robotic efforts of basic manufacturing in industry.

AFSC is responsible for R&D funding. Neither the operating commands nor the Logistics Command appear to have the responsibility or resources to do the research needed to satisfy their respective requirements. Moreover, without a center of expertise, there is nowhere to go to determine if robotics *could* help solve current or future problems.

When the Logistics Command determines it has a requirement for a robotic R&D effort, most of the time the requirement is related to the maintenance or supply functions, and comes under the heading of a "logistics need". The logistics needs are processed and approved through an activity of the Air Staff, and then form a basis for activity by the Systems Command. The logistics needs are collected and distributed yearly in a document entitled, "Air Force Logistics Research and Studies Program." The three volumes, covering "Research," "Development and Application (Emerging and Mature Technologies)," and "Study and Policy" have become known as the "Brown Books" because of their historic brown covers. If research is required, then one of the Air Force laboratories would be a likely candidate to investigate the feasibility of the task.

If research is unnecessary, and a commercial robot could be used to perform an Air Force task, there are other alternatives to fund the development and conduct the testing. The Air Force Productivity, Reliability, Availability and Maintainability (PRAM) Office can fund a test, and if there is appropriate payback in the project, then it will be approved. AFLC depots, with funding from the Depot Maintenance Industrial Funding, can procure commercially available equipment that can include robotics for depot operations. This approach has been used on a limited basis in the past.

The requirements process is driven by the operating commands and to date there has been no requirements "push" from them. The using commands generate the statements of need and participate in the validation, prioritization, concept phase, full-scale development, testing, and fielding. Without their backing and support, little will be accomplished.

AFSC has made a nominal effort in the MANTECH work with industry. The AFLC has made modest progress in dealing with their repair lines at the five ALCs through the underfunded REPTECH program. However, the operating commands, Tactical Air Command, Strategic Air Command, and the Military Airlift Command, have shown little interest in complementing or enhancing the weapon system acquisition process through the use of robotics in their operations.

Part of this lack of interest is "cultural." The "operators" have viewed robotic application in the context of the manufacturing process. However, we believe that future manpower shortages, hazardous operations, and CBR concerns, may raise their level of interest.

We therefore recommend the establishment of an Air Force Robotics and Automation Center (RAC) in a selected division of the AFSC. This division would have responsibility for all robotics

related R&D and automation applications in the Air Force. The RAC should consist of high level representation (civilian and military) from all divisions and include liaison with the other services, relevant DoD organizations such as DARPA, and NASA. The RAC would ensure intra-agency unification of the field and keep abreast of interagency related activities. We view this as realistic, though we recognize that some people believe robotics research should be centralized for the military in one agency. We also recommend that the services revitalize the Joint Technology Panel for Robotics (see Section 5.3.3).

In addition to this common research organizational structure, the Air Force shouid support the Robotics Artificial Intelligence Data Base (RAID), a source of information on military robotics, and establish standards so that parts can be interchanged and more easily repaired. All researchers should be provided access to ARPANET, MILNET, or similar networks for rapid communication and the sharing of ideas. The networks can be used to access RAID.

5.3 Technology Transfer and Exchange

The main reason to capitalize on technology transfer is to bring robots into use quickly and successfully. It would move the Air Force far up on the learning curve. The Air Force would profit from the successes and failures of other organizations and bypass the expensive learning cycle.

While the Air Force is not yet a major user of robots, the trend for the future, based upon Air Force manpower projections and the hazardous environment, is that the Air Force is heading toward a greater need and demand for robotics.

The Air Force can tap many sources of expertise when pursuing its robotics and automation programs, including:

- Industrial
  - Original equipment contractors/-suppliers
  - Other private sector manufacturing companies
  - Automation equipment and software vendors
- Universities and research laboratories
- Inter- and intra-agency
- National and international standards organizations
- Trade associations, trade shows, and publications
- Professional societies, technical meetings and research publications

5.3.1 Industry and the Air Force

The most obvious sources for technology transfer are the aerospace companies and other manufacturers who originally built the equipment that the Air Force maintains. Taking into account variations caused by differences between original manufacture and repair, the techniques they use in their plants could be applied to Air Force requirements.

Also, the grinding and painting expertise in the automotive industry should not be overlooked. Programmable robots can store several programs. Although the automotive industry runs only one program for high-volume work, the Air Force can run several programs and create a "high-volume" situation by combining part types or tasks.

Automation equipment and software vendors are another common source of technology transfer. They have many customers and applications and can draw upon a vast storehouse of information. Some robot vendors and systems houses will not only supply the robot but also take care of the grippers, programming, and systems. This arrangement would

reduce the risk to the Air Force, but would only be successful if the user organization participates fully in the planning and development to guarantee that the vendor understands the problem and that the system can be operated and maintained by the user.

Vendors funded much of the application development for the automotive industry. They perfected the robot or application and depended on repeat sales to justify the expense. In areas such as munitions buildup and aircraft servicing, the Air Force exercises an equivalent quantity-buy incentive and should be able to interest vendors in developing the necessary robots and peripherals.

Private companies help develop, produce, and maintain Air Force systems. Technology transfer from industry to the Air Force would be most practical and valuable in the Air Logistics Centers' manufacturing activities where there is a great similarity between the Air Force and other industries. A few examples are painting, grinding and deburring, welding, engine repair, hazardous material handling, machine tending, repetitive assembly composites manufacturing, and inspection.

We recommend: (1) a continuing Air Force-sponsored workshop on Air Force robotic needs that could be met by industry, (2) added subsidization of IR&D in this field to encourage industrial R&D activities in robotics, and (3) that vendors demonstrate that their systems have been designed to assist in robotic support operations.

5.3.2 Academe and the Air Force

Universities and research laboratories continue to be a primary source of technology and data transfer and this exchange of data should be further encouraged. Many universities offer joint industry and university research programs where the members select the direction of research and share in the results. The Air Force should consider using selected universities with established robotics, sensor, computer, and manufacturing programs to explore solutions to unique needs or state of the art applications. The Air Force centers of excellence established at Stanford University and the University of Michigan in 1982 have proved to be successful. These same universities could assist the Air Force in recruiting and continuing education programs. Graduates recruited from these programs who already are familiar with the research are a source of trained personnel. The Air Force Institute of Technology (AFIT) programs (research and academic coursework) in robotics should also be increased as a source of obtaining qualified personnel. We recommend additional efforts but on a more expanded scale, along the lines of the recently established NASA centers of excellence.

5.3.3 Interservice/Interagency Coordination

The Air Force application of robotics, automation, AI, and related needs for modern technology will continue to grow. Not surprisingly, similar needs have been recognized by the Army and Navy, other components of DoD, and other government agencies. Cooperation and exchange will help to avoid duplication, increase productivity, and save money. Several good examples of interagency cooperation already exist.

Military funding of manufacturing robotics development has primarily been by the Air Force. The intelligent task automation program funded by the Materials Laboratory at Wright-Patterson AFB and DARPA is demonstrating the application of vision to inspection, the control of precision operations through vision and tactile sensing, visual

identification of parts (even with a cluttered visual field), and automatic development of a detailed plan from goals. Two separate systems are being developed for the Materials Laboratory to demonstrate flexible assembly of airplane bulkheads. The concepts from intelligent task automation (ITA) and the flexible assembly systems will be applied to an Automated Airframe Assembly Center for the Materials Laboratory. The Navy has funded laser welding and cutting systems, a propeller welding system, and a large noncontact parts profiler. There are many open opportunities for increased cooperation.

The National Institute of Standards and Technology has built an Automated Manufacturing Research Facility (AMRF), in which they are developing communication standards, developing and organizing robotic control functions, and learning to control manufacturing processes at the global level. The AMRF, already emphasizing technology transfer, can be applied to military problems. The Air Force would benefit from the reduced costs that may be achieved by robotic manufacturing and should investigate the potential benefits of this liaison.

The Air Force should be particularly interested in robotic manufacturing of airframes, which are large, light-weight structures. The Navy shares this interest. If robotic operations can reduce the need for an inventory of expensive jigs and fixtures, there may be substantial savings. The Air Force should pursue this possibility.

The military does not yet use robots in construction although this is a rapidly developing capability in its civilian sector. The military could use robots to construct bases, and though the Air Force does not appear ready to use robots this way, consideration should be given to automated construction of bases. A more advanced use would be in the construction of space systems entirely by robots saving the cost and need for man in space. The Air Force should pursue this in cooperation with NASA.

Maintenance includes many separate activities, some of which can be handled by robots. The services are not yet pursuing major robotic maintenance demonstration programs, however, the Air Force may find robots useful to repair runways and deseal and reseal aircraft fuel tanks. The latter is a time-consuming task and a health hazard. The Air Force may also wish to work with NASA and the SDIO to promote the use of robots to repair satellites and work with elements of the Army and Navy on joint programs.

Material handling in the field involves primarily the supplying of fuel and ammunition. Distribution facilities at logistics centers are also subject to robotic automation. The Army has initiated a robotics program directed primarily at ammunition handling because of the large quantities of ammunition required during wartime. That program is developing robots to handle pallets of ammunition and does not apply to the Air Force because of differences in the ammunition. The Air Force may, however, wish to use robots at the logistics centers or develop specialized robotic systems for loading airplanes.

Robotics can save lives and make operations possible under hazardous conditions such as explosive ordnance disposal (EOD), in a CBR environment, fire fighting, and space operations. The Naval Ordnance Disposal Technology Center, Indian Head, Maryland, is responsible for military services research on EOD. Air Force requirements for EOD are not unique and the Air Force should continue to participate in the Navy program. The development process, however, remains long and priority is low.

The Army and the Air Force should share an interest in robotics for CBR operations at land bases yet neither has an active program. We suggest a joint program to develop a manned vehicle with a sealed cab and a teleoperated manipulator, perhaps under Army leadership, since their needs are more complex. The cab would protect an operator and the manipulator would perform the required operations. The U.S. Navy has a small program at the Naval Surface Weapons Center to develop fire fighting equipment for the deck of a carrier. The results of that program may be applicable to fire fighting at air bases. The Air Force should cooperate in the Navy program.

Robots for sentry applications would be autonomous vehicles that could patrol a base for intruders. The Navy is developing such a sentry robot at the Naval Ocean Systems Center. The Air Force should work with the Navy and support this program as well as the Army's work in this area.

Rapid technological growth often results in a shortage of knowledgeable personnel trained in the new techniques and applications, a lack of technical standards, and a series of heuristic solutions. Technology transfer, from R&D to military application, becomes particularly severe so that timely achievement of an operational capability is a major problem. Given that ten to 20 years can elapse before new technology finds its way into Air Force operations, the problem of technology transfer becomes critical (See Section 5.5). Compounding the problem is the need for extraordinary reliability and maintainability in situations that are environmentally harsh and unpredictable. Coping with this problem requires expert management, a high degree of cooperation among the organizational elements of the Air Force, and cooperation among the military services, in addition to achieving creative technical solutions.

The military services have an informal means of cooperation in the Joint Technology Panel for Robotics, sponsored by the DoD Joint Directors of Laboratories. This group seeks to increase the impact of robotics on tri-service technology as well as serving as a mechanism for coordination and information exchange. In addition, the Panel brings together representatives of non-DoD agencies to share experiences and to act as a focal point for the distribution of new activities in the very complex and fast-moving field of robotics and automation. Valuable though this panel is, it is informal and has neither the resources nor the staff to perform all the needed functions. Given the apparent overlap in the areas of interest among the three services in their effort to introduce robotics and automation, a higher degree of coordination is desirable. We recommend revitalizing this panel with line responsibility to work with the RAC previously recommended in Section 5.2.

5.4 Manpower and Skills

5.4.1 Air Force Personnel Profile-Current and Future

At the end of fiscal year 1987, the Air Force's population consisted of approximately 90,500 officers and 495,200 enlisted, a total of 585,700 uniformed persons. This force is augmented by a Reserve and Air National Guard Force (Total Force Concept) of 267,800. The uniformed force is further augmented by a Civil Service work force numbering 265,300. The total Air Force strength numbers approximately 1,118,800.

This total force is dispersed throughout the world at 133 active installations, seven major and 93 minor Air Guard and Reserve bases, and 1,070 other installations - 1,303 locations in all. Almost all officers (98.9 percent) have college degrees. Over 56 percent

have bachelors degrees, 42.3 percent have Masters degrees, and 1.4 percent have doctorates.

In support of its mission requirements, the Air Force operates and maintains almost 10,000 aircraft, supports another 10,000 foreign assistance aircraft, supports over 60,000 jet and reciprocating engines and over 1,000 strategic missiles. The Air Force is responsible for systems acquisition, R&D, testing, fielding, operating, and maintaining many complex systems. These include ground-based systems (over the Horizon Radar and North Warning radar system), many air-breathing systems (F-15/F-16, E-3A, and B-1B) and space based communications, and surveillance systems. The success of these development and support functions depends upon how well the personnel of the Air Force are educated and trained, initially and on a continuing basis.

The investment of the Air Force and other services in manpower is expensive. Historically, defense manpower costs, as a percentage of total outlays, has been about 50 percent. Personnel projections indicate that the eligible pool of 18 to 24 year olds will begin declining in the 1990s and could continue into the 21st century. Approximately 2 million people turn 18 each year yielding about 6 million 18-23 year old youths who are qualified and available. Following an already declining trend, there will be another 12 percent decrease in the numbers of this 18 to 23 age group during the period from 1984-1996. This projected decline, however, could be partially offset by:

- Women and immigrants entering the work force and competing for many of the same jobs as 18-23 year-old men. The resulting increase in unemployment in this age group could heighten their interest in the military.

- Cutbacks in federal employment and training programs has removed a source of employment opportunities and training that competed with military recruiting.

- Changes to the Social Security Act and tightening of the eligibility requirements for Social Security disability benefits. This is expected to increase the number of men over 55 who are in the active work force, and will decrease number of jobs available for younger men.

Nevertheless, the cost of manpower - both uniformed and civil service - will require productivity improvements for the Air Force during the next 20-25 years. Productivity enhancement, force reductions, and hazardous environment use should be the driving requirements for the introduction of robotics into Air Force operations.

More than 50 percent of the active duty and civilian jobs are technical in nature. The Air Force is encountering and will continue to encounter increasing pressure for the accession and *retention* of personnel in the high-tech fields. The civilian market for technical personnel will be in direct competition with the Air Force (both active duty and civilian) for personnel in these high-tech fields. Civilian technical sector compensation, entry level salaries, and longevity raises will increase faster than most segments of the economy, and will continue to outpace that of the military services. The retention of talented and well trained personnel will continue to be a challenge for the Air Force. The Air Force's civil service growth will be concentrated in the same occupational areas as private sector growth - scientists, engineers, computer specialists, financial and acquisition specialists. Recruitment and retention will be difficult at all grade levels in the Air Force civil service force. This problem will be further compounded by the continued reduction in the number of scien-

tific, technical, and engineering graduates (and dearth of U. S. nationals in scientific graduate study programs) from U.S. universities and colleges. Engineering enrollments at U.S. colleges and universities are declining due to demographic changes and reduced interest in engineering and science in recent years. Freshman applications at some leading schools have been steadily declining over the past few years (7 percent per year). A loss of 30 percent in science enrollments from 1983 through 1987 and a 10 percent decline in engineering in 1987 have been experienced at many leading universities.

Finally, the manpower problem is further compounded by the fact that approximately 60 percent of doctorates in engineering are now awarded to foreign nationals, many of whom are forced to leave the U.S. against their wishes upon completion of their education - a clear export of technological talent. On the other hand, it is estimated that by 1992, nearly 90 percent of faculty at U.S. universities under the age of 36 will be foreign born.

5.4.2 Effect of Robotics on Requirements

Robots and AI reduce manpower requirements. However, a new cadre of highly skilled people will be needed to purchase, install, and maintain the new equipment, and to provide training to users. Users will need adequate engineering background or technical skills or both. New recruits with a more technical background will be needed and existing personnel will be have to be retrained. Most importantly, retraining will be a continuing requirement since technology in this field changes rapidly. The Air Force needs to ensure the programs are established to provide the initial and continuing education and training that will be required.

The technologies required to effect recommended robotic applications can be successfully applied only if the Air Force embarks on an aggressive initial and continuing education and training program.

5.4.3 Educational Needs - Universities and Air Force

Robotics is an interdisciplinary field. Clearly, not every technical person in the field must be knowledgeable in all areas, but it is essential that all the areas be covered among the technical personnel. We regard the major fields to be electrical engineering, computer science and engineering, mechanical engineering, and systems engineering.

Fundamental to satisfying these requirements is the appreciation of the need for basic or initial education coupled with ongoing continuing education. The latter needs a real boost in the Air Force in general. The need to retain qualified personnel with degrees, especially those with doctorates and with technical expertise in robots, is mandatory.

A clear distinction must be made between education and training. The services should depend upon the existing university structure for basic and advanced education. This should be supplemented with on-the-job training. Continuing education responsibilities should be shared between the Air Force and university sector. The Air Force should take advantage of courses offered now by many universities at satellite facilities. Finally, systems integration and interdisciplinary education should be stressed, since many needs are application driven.

Universities can respond to Air Force manpower needs in robotics, and should be better utilized. First, those universities with established robotics

curricula can provide the complex, multidisciplinary education required in the field at the undergraduate and graduate levels. Second, universities can and are now providing on-base or satellite delivered educational programs to enable both military and civilian Air Force personnel to obtain advanced degrees. Certificate programs emphasizing robotics and related technologies are also available. These programs should be better utilized.

Presently, the broad potential of robotics in the field of logistics is virtually unknown on university campuses. Furthermore, the magnitude and technology spectrum represented by logistics is generally unappreciated by faculty and students alike. It is therefore not surprising that young people are not aggressively pursuing careers in logistics. Overall, better Air Force use of current offerings of universities is called for, and the opportunity exists for Air Force enhancement of this sector as well. Air Force ROTC programs would do well to organize ongoing design projects on campuses to attract and motivate undergraduates.

The Air Force should develop training programs to supplement those offered by universities to include the continuing education of personnel in operational duty areas, overseas, and on bases far from major schools. A "master class" could be developed at the AFIT or other centers to train teachers in this specialized area of robotics and automation.

Training for operation and maintenance of robotic systems presents particular difficulties because of rapid innovation and obsolescence in the field of robotics. The most common method of obtaining expertise in the operation and maintenance of new systems is to send personnel to courses provided by manufacturers or to contract with manufacturers to teach courses on base. Selected universities might help with "engineering technology" programs. The "systems" aspects of maintenance are particularly difficult to learn. Here again, it may be necessary to develop master teachers, and to provide them with continuing opportunities to acquaint themselves with new technology as it becomes available. Updating and retraining will be a continuing requirement.

A large military organization is not well suited to adapting rapidly to technological change. The time required for orders to flow through the chain of command is relatively long compared to the time constants of changes encountered in robotics, AI, and other highly computer-intensive technologies. The Air Force procurement cycle is so long that technology may be obsolete before it is purchased, placed in service, and personnel trained to operate and maintain it. The challenge is to develop educational and training programs coupled with faster procurement cycles to ensure that the best contemporary technology is available for the nation's defense, that the people who will specify, purchase, operate, and maintain it are provided with necessary education and training to remain current in the technology.

Many of today's senior designers received their earlier education with little or no consideration for robotics. Institutions of higher learning are controlled by senior educators who are not very knowledgeable in robotics and consequently do not stress automation in their respective institutions design curricula. A new approach is required both in industry and academia. A major effort is required to include automation and robotics as a standard design consideration in the design process. In the Air Force this can be achieved by placing a higher level of activity on robotics R&D. Academia and industry

respond to increases in R&D efforts, and the necessary education and re-education programs should follow.

The same historical problem pervades the engineers in the Air Force. Many were not taught about robotics or "brought up" in the technology and it is "foreign" to them. The engineers in the AFSC must be trained and educated to recognize the potential for robotics in new system design and in the development of specifications that include the consideration of robotics in system design. They must design for robotics and learn how to evaluate proposals and alternative designs that include robotics aspects.

Additional training and education for operating command personnel will necessarily focus on the operation and maintenance of the robotic systems. For some maintenance officers this may be a philosophical problem. Controlling work through automation and robotics is intellectually different from ordering maintenance personnel to perform tasks. However, the maintenance community adapted to the automation of test equipment and can readily adapt to the additional automation of maintenance tasks with the proper education. A program to develop awareness of the potential benefits of robotics is necessary.

The impact of any additional automation is always associated with the complications of the socio-economic issues. Robotics is no exception. The totality of the change needs to be determined before implementation begins. Within the AFLC depots, the work performed by robots is generally not considered enjoyable. Replaced personnel are afforded a retraining program that has the potential to improve career paths for the workers. (Robots can also replace personnel through attrition.) The operating commands have readily embraced the mechanical materials handling equipment in their supply and transportation systems. They continually use "automatic" test equipment in everyday activities. Although the operating commands probably do not think in terms of having started in the direction of robotics, they have used automation where it has helped their operation and they should continue to do so.

There will be some changes in maintenance activity and these changes will affect personnel. Most of the proposals for automation in the operating commands show manpower savings. Often the savings are achieved in planned wartime operations where insufficient personnel are available. The effect of robotics allows the wartime capability to be fully performed. The assembly of drop tanks is an example where personnel resources are not available to furnish drop tanks for every mission. With robotic assembly aids, this should be possible. The price of robotics for the operating commands is the care, maintenance, and transporting of the robotic system. If robotics systems are designed to be light, strong, portable, modular, and easily reparable and maintainable by existing personnel, then the addition of robotics at the operating command is minimal. Robotics applied to tank assembly would increase wartime sortie capability and reduce personnel requirements for the operating commands.

One major impact of robotics in the depots will be the migration of workload from the current standard depot tasks of planning, programming, modifying, and supporting various robots. Many routine functions will be reduced or eliminated, particularly those activities involved in potentially hazardous environments. Many jobs requiring worker proximity to toxic chemicals, sprays or dusts will largely be automated. The design, development, and support of automation systems and the robots will be an added workload. This migration of workload will require changing skills and it is

doubtful if all or even a significant number of the workers will be retrainable for the new effort. The overall impact, however, should be a reduction in the work force combined with an increase in personnel technological skills and knowledge.

5.5 Market/Technological Lifetime Time Constant Incompatibilities

It is necessary to compare the relationships among the technological time constants, the time to market, and the lifetime of a component, product, or system, and consider these from the perspective of Air Force weapons systems and components.

The technological time constant is the half-life of the key technological component of a product or military system. Consider the personal computer, for example. It has a key technological element: the microprocessor. To gain some perspective for the key technological time constant, consider that microprocessor development began in 1972 and has already evolved through four generations (4-bit, 8-bit, 16-bit, and 32-bit). The technological time constant for this product is approximately four years. To effectively compete and market a PC, one needs a current microprocessor chip. Product effectiveness depends on the relationship between the time to market the product and the key technological time constant. If the time to market greatly exceeds the technological time constant, the product will not be competitive. For example, a 4-bit microprocessor-based PC marketed today simply could not compete with the 16-bit and 32-bit machines now available. The product lifetime in turn depends on the technological time constant and to some degree should be related to the time to market as well. One would like to have a product lifetime that is at least comparable to both the technological time constant and time to market or which greatly exceeds either or both of them. It would not be sensible to market a product that takes two years to develop if its product lifetime is only a year because of obsolescence.

With respect to the Air Force and its "products," one can look first at the product lifetime and cite such examples as the C-130 and the C-5A, which are now approximately 32 and 20 years old, respectively, since they were designed. The F-16, which took about eight years to become operational, is inherently a more complex system and several key technological time constants are involved. Rather than detail the individual technical components, it is sufficient to note that the rate of technological change has been rapidly increasing over the last few decades. The time to deploy an operational system within the Air Force has not kept pace with the shorter technological time constants. Consequently, because there is a need to keep the product lifetime at least equal to the time it takes to field an operational system, we find ourselves working for 10 to 15 years to put a weapon in the field and maintaining it for at least that long. It is not surprising that we find systems in the Air Force that are 25 to 30 years old, using antiquated technology, or with systems that have been incrementally upgraded through design changes over the years because of their long operational lifetimes. This situation is becoming worse and is only tolerable because of the lack of competitive atmosphere within the service itself, unlike the industrial sector.

There is, of course, the serious question of whether complex Air Force systems can be produced in less time. Our own industrial sector produces commercial airplanes in a shorter time than is experienced in the DoD acquisition process. The U.S. military has also proved equally capable of producing complex aircraft in a shorter period of

time during an emergency or surge situation (wartime).

In the absence of significant driving forces motivating accommodation to rapid technological change, coupled with the lack of a highly competitive environment, the time to produce an operational system in the Air Force and the associated product lifetime is inordinately long. Solving this problem presents a significant management challenge to the Air Force.

5.6 Design for Robotics

In the expression "Design for X," *X* has been defined as many things, including the "ilities," which include maintainability, reliability, and manufacturability. In the context of this study, we are most concerned with the basic mentality and underlying philosophy involving design for robotics and automation. Concurrent engineering design goals are also necessary.

Implementing automation and robotics from the ground up, having it permeate the entire product and process, is easier than doing it incrementally.

To incrementally adapt to automation and robotic processes a system, function, or machine that has been under manual control or operation is quite difficult. The required sequential upgrades would create almost as many problems as perhaps the redesign of the process or the system from the start. Several examples exist. The General Motors production line for the successful Cutlass automobile was a completely new facility developed specifically for the production of the Cutlass. The facility incorporated distributed computerized data bases and complete robotic lines for welding and inspection. Other examples involving Computer Integrated Manufacturing (CIM), such as those at AT&T, Allen Bradley, among others, are cited as milestones in terms of a CIM facility. For the most part, they have been approached from a total CIM standpoint rather than incremental CIM. The same philosophy and approach should apply to the complex systems in which the Air Force is involved.

People involved in system design must be imbued with an attitude toward robotics and automation that strongly supports the integration of design, manufacturing, evaluation, and application of robot systems. This integration would use a fully integrated automated design developed from a common data base.

We therefore recommend that the Air Force establish a pilot program that picks a representative product or system (perhaps in the composites area) to which the overall concept of automation and robotics would be applied from the conceptual design phase through the production of the final product. This program would be a valuable product vehicle and could serve as the basis for the product of the future.

Also, to demonstrate the value of overall integration of robot technology, we propose that the Air Force establish an advanced logistics facility that incorporates automation and robotics applied to the logistics problem.

6.0 CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

It became clear during this study that two diverse factors must be addressed before the Air Force can successfully benefit from robotics. The technology issues - robots developed or adapted to meet Air Force requirements - are a primary consideration. Equally important, though, are the organizational and operational issues that must be resolved.

We believe that both areas must receive equal and sufficient attention; the combined effect vastly exceeds the results obtainable from either factor alone. In addition, we conclude that obtaining a "critical mass" of effort is necessary and accelerates subsequent paybacks; isolated or token activities have negligible impact.

Consequently, the committee has drawn three major conclusions based on the information made available to us during the course of the study:

- Robot technology can be effectively applied to respond to Air Force needs.
- The Air Force is not aggressively using or developing robot technology.
- A central focal point within the Air Force, to champion the use of robots, is essential if the full potential of robot technology is to be realized.

6.2 Organizational and Operational Issues

The tasking to this committee with its broad latitude for our inquiry has permitted us to emphasize what we perceive to be critical philosophical and organizational challenges and management issues within the Air Force (see **Figure 6-1**). These challenges must be met and the issues resolved if the Air Force is to be successful in development and integration of automation and robotics to meet its requirements.

Organizational-Policy Recommendations

The introduction of widespread use of robots into the existing Air Force environment will require understanding, persistence, and a willingness to change. The single most important conclusion drawn from this study is that there must be an organizational focus at both the individual facility level and at higher levels. Section 5.0 lists many organizational opportunities, which are summarized as follows:

- Identify and support substantive centralized and organizational focal points for leading robotics activities.
- Revitalize inter- and intra-service communication and coordination to include the Joint Technology Panel for Robotics.
- Use interagency data sharing and coordination of R&D.
- Participate in university research programs, workshops, and conferences.
- Strengthen ties with universities and sponsor robotics courses.
- Solicit technology transfer from applicable industries.

Manpower and skills are another organizational issue. Recommendations include:

- Improve programs to attract and retain talented personnel.
- Improve training and education programs in robot technology areas.
- Establish continuing education programs with universities to obtain higher skill levels.
- Define career paths in the disciplines necessary to support automation and robotics.

Operational Recommendations

The committee uncovered two crucial underlying conditions which, if not successfully resolved, will hinder the chances of success: technology/lifetime time constant incompatibilities and design for automation.

With respect to technology/lifetime time constant incompatibilities we recommend:

- Reduce the delay between technology selection and actual procurement.
- Redefine system obsolescence and replacement criteria.

Design for automation is even more pervasive and deserves high level attention. The report stresses several recommendations:

- Establish "design for automation" policies and procedures for all new products and equipment.
- Implement a pilot program that incorporates robotics consideration from design through production.
- Establish a corresponding advanced prototype logistics facility incorporating robotics and automation for all major logistics functions.

The above recommendations are based on current activities and practices within the Air Force. The rapid changes in technology, however, coupled with the slower ability to implement the technology within the Air Force, prompts the committee's additional suggestions to:

- Support frequent in-service reviews of robotics progress and impediments to achievement of goals.
- Consider periodic reviews of Air Force direction and opportunities in robotics.

6.3 Applications and Technology

The committee has not reviewed any Air Force programs used in the field of combat operations such as remotely piloted vehicle (RPV) programs or smart weapons. We specifically excluded the use of robots in a direct combat role and instead looked at the potential uses of robots to support combat and logistics operations.

Based on the results of our study, we conclude that there are application and research areas where the Air Force can and should place immediate emphasis. Further, resources should be dedicated to achieving enhanced robotics capabilities. The following summarizes and highlights the views expressed in previous sections of this report. Our recommendations are outlined in **Figure 6-2** and divided into two areas: organizational and technical. Within the organizational area we provide recommendations derived from our philosophical and attitudinal discussion in Section 5.0.

Recommended Applications

Our recommended robotic applications (see **Figure 6-3**) fall into three categories; for the short term, those that have a common basis with commercial applications, those that require adaptation of current technologies and limited research to meet specific Air Force needs, and for the long term, specific Air Force applications that require significant research. We believe

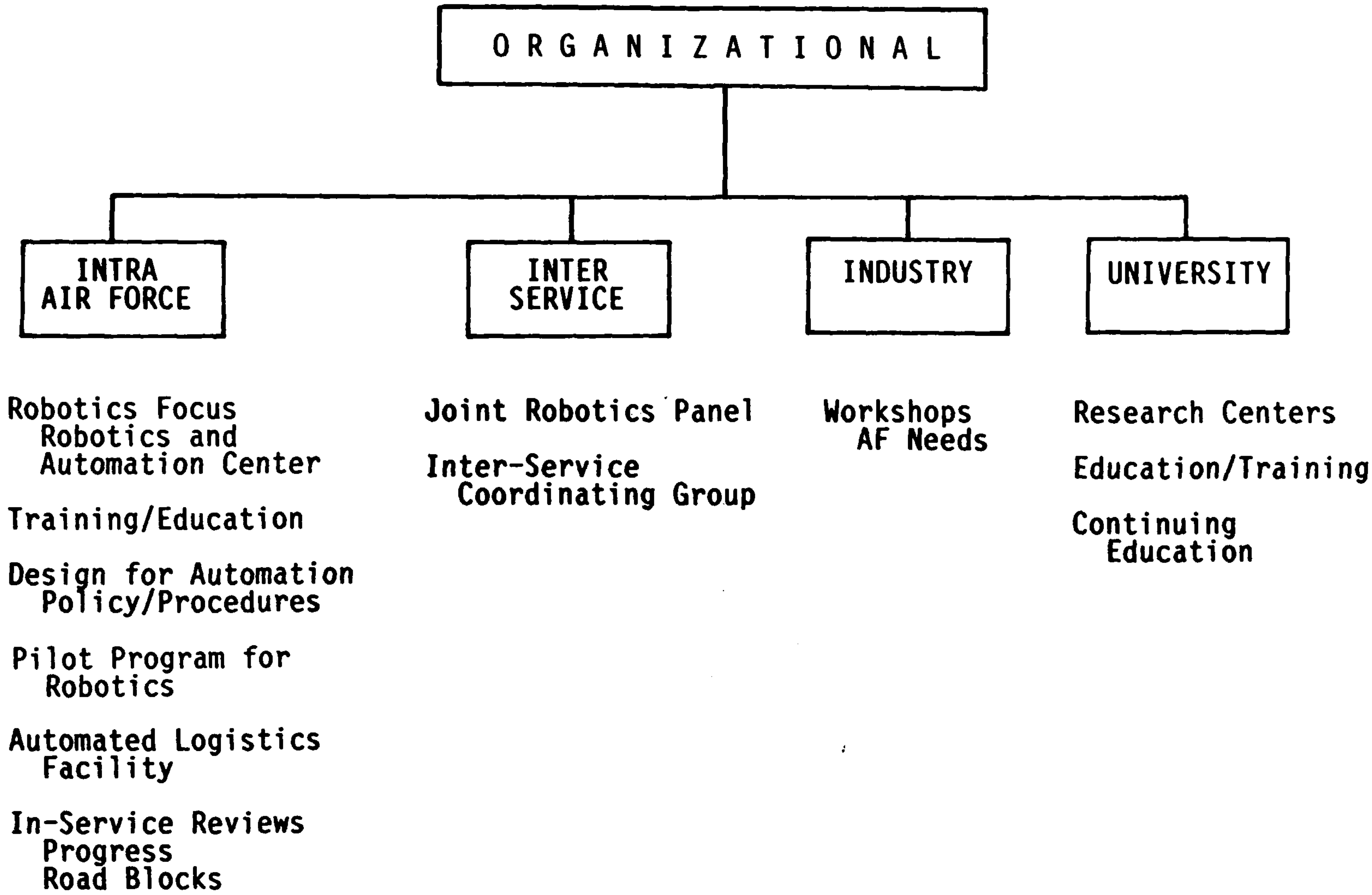

FIGURE 6-1 ORGANIZATIONAL

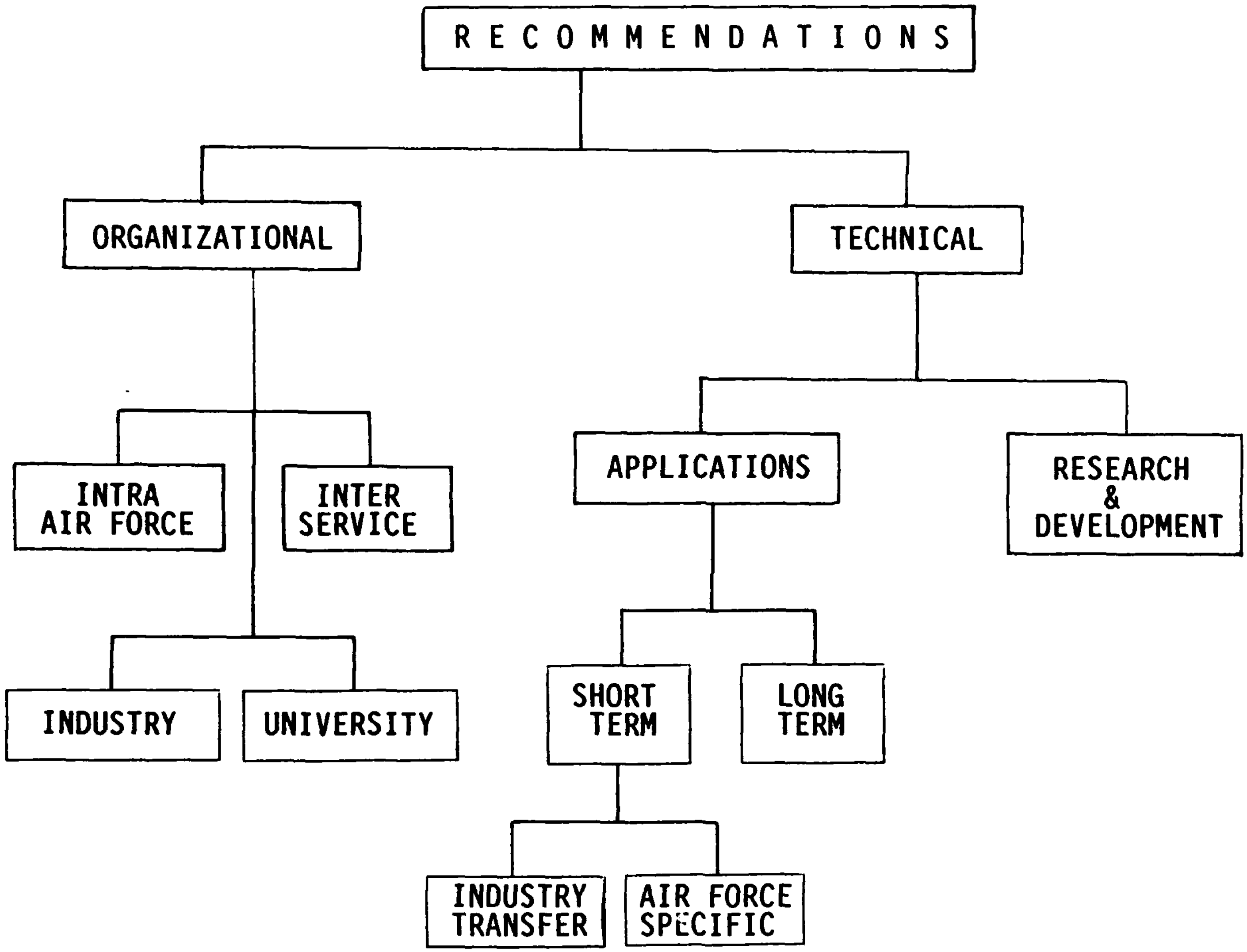

FIGURE 6-2 RECOMMENDATIONS

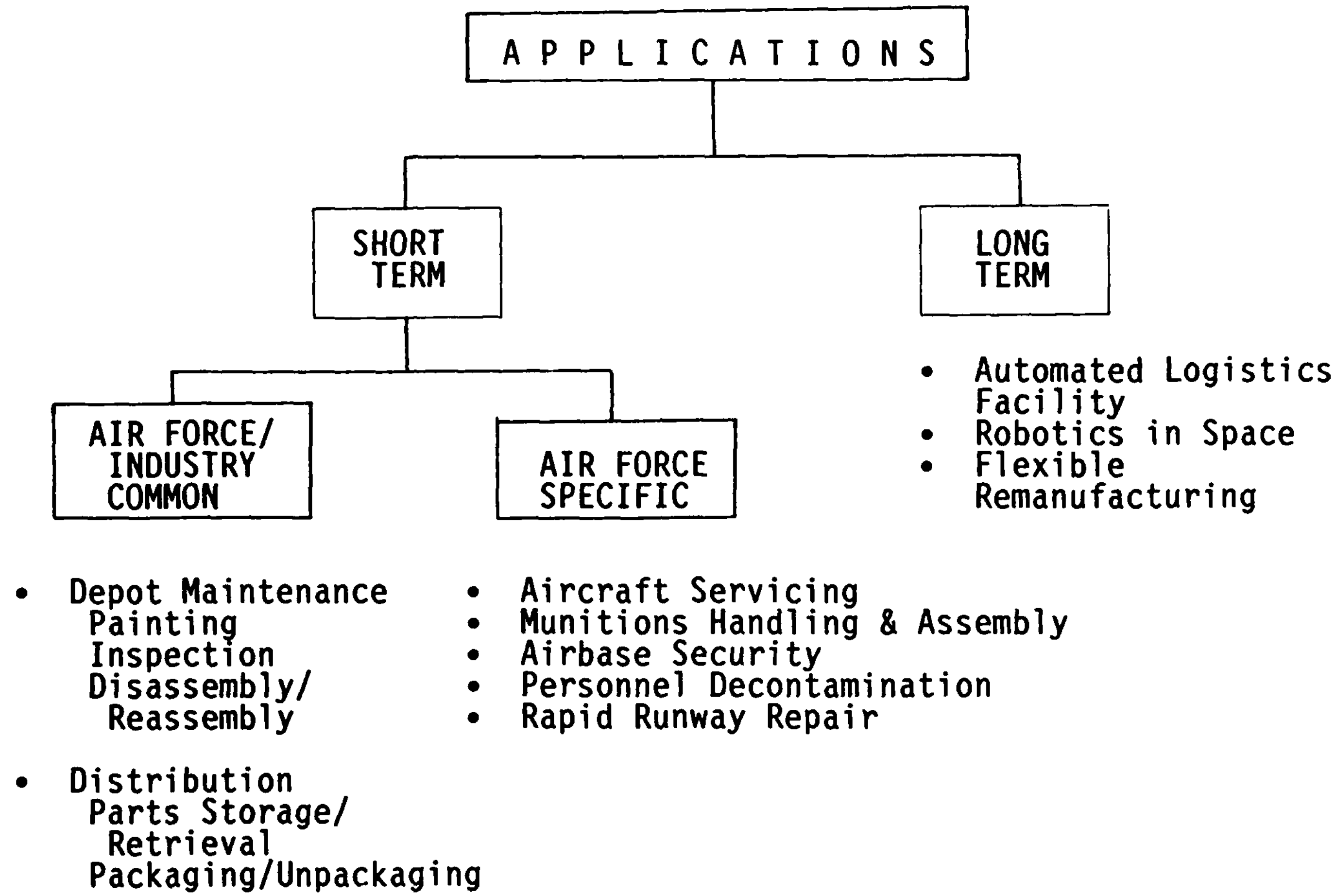

FIGURE 6-3 APPLICATIONS

that action can and should begin immediately in each area.

Further, the selection criteria discussed in Section 3.0 should continue to be applied by the Air Force over time, to uncover new opportunities.

The committee has not developed a strategic plan to implement the recommendations of this report. The need to address implementation through such a plan is clearly recognized, but is inappropriate here. The initiative properly lies within the purview of the Air Force.

Commercial Robotics Adaptation. Many Air Force requirements have a common basis in the commercial world and involve depot maintenance and resupply functions. For these types of applications, the Air Force should concentrate on transitioning technology from the commercial world and adapting it to meet Air Force requirements.

a. Depot Maintenance. Examples of specific applications are:

- Aircraft Painting
- Component Painting
- Automated Inspections
- Wheel & Brake Disassembly, Reassembly
- Engine Disassembly, Reassembly

b. Distribution (Supply and Transportation). Supply and resupply, packaging, handling, storage and retrieval of components for shipment have close parallels between the Air Force and the commercial world. The Air Force should readily adapt and expand upon commercial technologies that deal with package handling.

Recommended applications are:

- Automated Parts Storage and Retrieval
- Automated Packaging and Unpackaging

Air Force Specific Requirements - Short Term. Many Air Force requirements for robotics are significantly different than commercial applications because of the functions performed, mobility needs or peacetime preparedness requirements while maintaining combat capability. Required functions that do not have a commercial equivalent include: assembly and loading of weapons, the resupply of expendables in space, rapid mobility needs to support aircraft operations and combining peace-war functions.

High payoff functions could be developed to meet Air Force needs with limited research by adapting research to Air Force unique problems. Short term initiatives fall into two natural groups: those important in both peace and war, and those critical during wartime. The study found these applications to have the highest potential in both peace and war:

- Aircraft servicing
- Munitions assembly and handling
- Air Base security

Applications relatively unimportant in peace but selected due to their possible importance in war include:

- Personnel and equipment decontamination
- Rapid runway repair

Air Force Specific Requirements - Long Term. There are major Air Force application needs for robotics which have little direct commercial equivalent or any known near-term solution with limited research and development. These

applications will require basic research or long periods of applied research. The strategic importance of the applications, however, dictates that research be done and not postponed or avoided.

We identified three Air Force specific applications where the benefits of using robots warrants the R&D associated with their accomplishment:

- Ground logistics redefinition, based on a total automation and systems concept for major surge capability with little cost penalty
- Space logistics using robots, considered essential for vehicle replenishment, rework, repair, and upgrades of space assets
- Flexible remanufacturing, particularly the reduction of jigs and fixtures by means of data base control of light machining operations

6.3.2 Recommended R&D

Design and fabrication of robot systems to meet Air Force requirements will draw upon a variety of technologies. These enabling technologies are summarized below with recommended requirements for R&D efforts. **Table 4-A** in Section 4.0 shows the correspondence between recommended applications and recommended R&D technologies.

a. Computer Control Systems

- Formal models for hierarchical control
- Next generation intelligent software technologies
- Distributed, parallel, supercomputer architectures

b. Sensor Systems

- Resolve conflicting sensor information
- Improved capabilities across all sensor types
- Common interface specifications

c. Actuation Systems

- Multi-criteria control of modular lightweight serial and parallel architectures
- Physical plant modeling in real time software
- Adaptive control for process disturbance rejection

d. Human Interface Systems

- Balanced human and computer control
- Human intervention at higher decision making levels
- Stand-off operation of many remote robot units

ACRONYMS

AAAC	automated airframe assembly center
AD-DA	analog to digital-digital to analog
AFESC	Air Force Engineering Support Center
AFLC	Air Force Logistics Command
AFML	Air Force Materials Laboratory
AFOSR	Air Force Office of Scientific Research
AFSC	Air Force Systems Command
AGV	automated guided vehicle
AI	artificial intelligence
ALC	Air Logistics Center
AMRF	automated manufacturing research facility
APPL	automated paint and process line
CAD/CAM	computer-aided design/computer-aided manufacture
CB	chemical/biological
CBR	chemical/biological/radioactive
DARPA	Defense Advanced Research Projects Agency
DoD	Department of Defense
DOE	Department of Energy
DOF	degree(s) of freedom
EOD	explosive ordnance disposal
ERAM	extended range anti-tank mine
EVA	extra vehicular activity
FTS	flight telerobotic servicer
ITA	intelligent task automation
MANTECH	manufacturing technology
MFFR	Multi-function fabrication robot
MIMD	multiple instruction multiple data
MIPS	millions of instructions per second
MSCM	mechanical systems condition monitoring
NAVEOD	Naval Explosive Ordnance Disposal
NC	numerical control

NDI	non-destructive inspection
NIST	National Institute of Standards and Technology
NSIA	National Security Industrial Association
OMV	orbital maneuvering vehicle
ORU	orbital replacement unit
PWM	pulse width modulation
R&D	research and development
RCS	real time control system
REPTECH	repair technology
RFI	ready for installation
RFP	request for proposal
ROM	read-only memory
RPV	remotely piloted vehicle
RRR	rapid runway repair
SBI	space-based interceptor
SIMD	single instruction multiple data
SPO	system program office
SSTS	space surveillance and tracking system
UXO	unexploded ordnance
VLSI	very large scale integrated
V-MOS	metal oxidized semiconductor with a V-shape geometrically etched into it
VTOL/STOL	vertical take-off and landing/short take-off and landing

GLOSSARY

bus a communication structure network inside a robot, similar to a multiple outlet extension cable.

degrees of freedom The number of independent inputs required to control the output of the robot to provide desired motion or force functions or both.

end effector The tool, gripper, or hand at the output of the robot manipulator that does the work.

flexible manufacturing an automated manufacturing system that can be changed product by product without major modification of the machinery.

kinesthetic The physical interaction of the human through the muscle system (e.g., hands, legs, shoulder) to command the robot to do the desired task functions.

parallel architecture A geometric arrangement of links and joints where all inputs act together to create a desired output by operating in similar substructures. The legs of a spider form a parallel structure).

serial architecture A geometric arrangement of links and joints where all inputs are additive (one link, one joint, one link, etc.). The sequential actuations associated with finger motion are an example.

teleoperation The coupling of human commands (voice, kinesthetic, etc.) through computer transformations to drive a slave robot to perform a desired function, sometimes with full human intevention and sometimes in a supervisory manner.

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APPENDIX A: SUMMARY OF ROBOT TECHNOLOGIES

The definition for robotics adopted for this study (see page 1) suggests a breakdown of the technologies associated with this emerging field. To expand on this implied breakdown, the summary proceeds hierarchically in terms of four major technologies, each with several component technologies. These technologies, computer control systems, sensor systems, actuation systems, and human interface systems are discussed extensively. To better understand the level of today's technology, a condensed version of a fifth generation concept of robotics and its potential application range is provided. An overview of each major topic is provided, followed by a summary of its associated component technologies, highlighting the current level of technology. This is followed by a thorough technical description of these system and component technologies.

ROBOT TECHNOLOGY TODAY

Robotics today is dominated by industrial applications where simple, repetitive tasks are done reliably at relatively low cost. Most of these tasks are transfer operations moving products between machines that have specialized characteristics to produce high value in the product. The principal attribute of today's robot installations is their long life (20,000 hours is the norm). This need for high reliability has forced designers to be conservative in the integration of modern technologies. Hence, the equivalent of fly-by-wire technology in our advanced aircraft is not represented by a similar technology of a fully modeled and adaptively controlled dynamic system with aggressive computer (or human) decision making for critical operation of the technology at the highest possible level.

It is frequently argued that industrial robots weigh too much (some weigh more than 5,000 lb.) for the payload they carry, have poor dexterity compared to humans, require costly supporting equipment (jigs, fixtures, feeding mechanisms, and extensive engineering integration time and costs), cannot adapt adequately to changes in their environment (only a very limited use of force sensors and in some cases vision sensors), and cannot respond to process parameters (force disturbances cause deflections 20 times greater than their basic resolution).

All of these contentions are valid to varying degrees depending on the application. Robotics is a remarkably incomplete technology compared to the accelerated growth of technology for aircraft, C^3, and telecommunications. Though the highest quality of position encoders is found, their integration into an architecture of robotics is an afterthought. The geometry of today's robots resembles a lightweight numerical control (NC) machine or a human arm and this leaves much of the potential architecture of these systems untouched or very poorly understood. Electric prime movers used in these systems were designed primarily for much less demanding applications; hence, their high weight, poor responsiveness, and low adaptability. The architecture of computer controllers tends to be that which was frozen around 1975. Certainly, computer technology is being developed, but only incidentally for implementation in robot systems.

The state-of-the-art in robotics is very application-specific and lags behind the general technical developments of other fields. An enormous opportunity for technical growth exists and an aggressive national development program is not only desirable but essential to meet current and future industrial and military applications.

ADVANCED ROBOT TECHNOLOGY

The concept of an advanced (fifth generation[1]) robot technology represents full integration of the most advanced computer technology with general mechanical architecture (serial, parallel, and modular) to demonstrate an electronically rigid system (similar to our latest fly-by-wire aircraft) capable of rejecting process disturbances in real time while producing high value-added products on demand. Today, high value-added operations are done with expensive, specialized, and dedicated machines such as NC machines, automatic screw machines, and wire bonding equipment for microcircuits, where the robot does the low-valued function of handling parts between these dedicated machines. By contrast, the fifth generation robot would be a fully integrated and self-contained generic machine system capable of performing a wide spectrum of precision light machining operations completely programmable by the designers of the product (shoes, clothes, and appliances) and fully responsive to the individual demands of the marketplace. This vision of robotics by Isaac Asimov is the heart of the factory of the future, yet it not only does not exist, technical resources to make it possible either are in short supply or have not been concentrated in a sufficient critical mass of expertise to make it happen.

Beyond the factory of the future, robots can be used in hazardous environments, such as space and ocean floor operations, ammunition handling under chemical or biological attack, processing of dangerous materials such as gallium arsenide for advanced microcircuit technology, and nuclear reactor maintenance. Also, special applications of real value to society, such as microsurgery, have yet to be dealt with except in the research environment. The concept of the fifth generation robot suggested here would lay the foundation to demonstrate a science of intelligent machines sufficiently general to treat all of these diverse and rewarding applications.

The following is a partial list of applications that would become feasible or would be dramatically accelerated by an aggressive development of a fifth generation technology:

1. nuclear reactor maintenance
2. precision light machining
3. micro-manipulation at very small scales
4. microsurgery
5. ocean floor operations
6. space station operations
7. battlefield operations

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[1]This concept of an advanced robot is equivalent to the fifth generation robot system (1995 on) in comparison to the third generation (real time dynamic model reference control, 1980-1995) and the fourth generation (modularity in both hardware and software, 1985-2000).

8. 50G centrifuge robot
9. rapid runway repair
10. remanufacture of military hardware such as jet engines and airframes
11. walking machines and cooperating robots
12. human augmentation for the handicapped

TECHNICAL OBJECTIVES OF AN ADVANCED ROBOT TECHNOLOGY

Over the past several decades the electronics, computer science, and software research communities have made major strides forward in their technical depth, especially enhanced by strong pulls from the civil and defense sectors. The massive technological growth in microelectronics is obvious. Emerging technologies such as artificial intelligence (AI), computer architectures (neural nets and parallel processing), simulation workstations, and machine vision, leads to the conclusion that new opportunities exist to expand the system technologies of robotics itself. Nonetheless, until dedicated architectures have been targeted just to the exceptionally complex system of robotics, little will be achieved. For example, though "expert systems" are being made available to enhance the decision making process, an examination of the requirements for robotics reveals hundreds of complex computational criteria, most of which are yet unknown. The reality of this class of task is heightened if there is a requirement for a prioritized decision among these criteria in less than 30 milliseconds.

By contrast, mechanical technology has not kept pace and because of this it is now perceived as a weak partner. Unfortunately, the mission objective of intelligent machines will require a marriage of many of these technologies, including the mechanical. Much of the mechanical design philosophy in the United States derives from a period during which farm machinery, power plants, construction machinery, automobiles, airplanes, and jet engines were brought to a high level of development. Much of this design is done in terms of compartmentalized rules (the basis of an art and the opposite of a science) that are based on negative criteria (noise, wear, fatigue, instability, vibrations, and mean-time-between-failures). On the other hand, the factory of the future demands the use of operational criteria associated with the quality of the machine's product which implies precision (rarely dealt with as a first priority in the academic world). The positive criteria of precision involves the control of the output of the machine to specified tolerances regardless of the disturbances generated by the operation. To date, not a single robot operates in terms of a real time dynamic model based on an accurate description of its system parameters to reject disturbances. Furthermore, the negative design criteria of failure in the operation of large machine structures of the past (textile machinery and battlefield material) have little to offer for the design of precision microprocessing equipment on a scale suitable to microsurgery or microcircuits. Hence, for the level of technical integration required to meet future needs, no balanced science of intelligent machines is being developed.

Similarly, no industrial robot operates in terms of a real time dynamic model description to close the loop relative to the process it is performing and which may generate significant disturbances in the system. This means that precision light machining operations such as drilling, routing, and milling cannot be done by reasonably sized generic robots to the required level of precision. Disturbances due to forces equivalent to the specified load capacity of these robots can easily cause a deflection 20 times greater than the error represented by its repeatability (i.e., a 20 to 1 robot). The goal must be to measure these disturbances and to compensate for the resulting deformations

(to maintain the desired level of precision) by means of a complete dynamic model evaluated in less than 10 milliseconds (real time) by using the most modern computational hardware and software. This class of control would be equivalent to feedforward (opposite of feedback) compensation (a technique now found in the very best Japanese audio equipment) and is what is meant by an electronically rigid robot system.

DESCRIPTION OF CURRENT ROBOT TECHNOLOGIES

A-1.0 Computer Control Systems

The computer acts to coordinate and balance all functional activities in the robot. These functions are increasingly non-deterministic and may represent widely varying choices to meet task requirements. These requirements may be derived from on-line access to a data base or they might come directly from human intervention. Some task requirements will require global task planning while others will require meeting precision motion specifications while being influenced by significant internal or external disturbances. Because of the highly nonlinear and highly coupled nature of the mechanical structure, feedforward modeling is needed to integrate high level sensory information, compensate for deflections, avoid obstacles, and do multiple arm tasks. Hence, computer hardware and software are at the heart of the operation of all robot systems.

In a complex task environment, the robot would have a multispectral sensor system, which is connected to a complex actuator system. The control section would consist of multiple networked computers using communications technology to maintain a distributed data base that represents a world model. The computer would formulate and evaluate alternative action plans, monitor the execution of current plans, and coordinate the actions of what were previously considered as several robots. The controller would use the best AI techniques married to data base, communications, and network technology all built on advanced computer systems and using the latest technology.

A-1.1 Hierarchical Control Systems

Summary: Because there are many layers of functional activity (sensors, actuators, end-effectors, localized disturbance rejection, and sensor data integration), it becomes essential to create a formalism to structure decision making and control, i.e., hierarchical control. For example, at least a decade of activity at the National Bureau of Standards (now the National Institute of Standards and Technology or NIST) has resulted in a modular, layered, parameterized format to prescribe interaction above, below, and within each layer with assignable time constants. These layers may be in parallel or in series depending on the larger system architecture. Their interfaces are well defined and standardized.

Description: The development of robot control systems has advanced significantly since the days of the first robots. These early devices were controlled in some cases by simple relay logic systems and had very limited capability. With the advent of computer controls came the simultaneous development of levels of control. In the early versions of control levels, one thought of three levels of control. The first and simplest level was for the operator of the robot, which allowed for minor modifications of the robot "program" and typically was achieved by providing tubular data to the program. A second level of control was achieved by the "applications programmer" who developed

computer algorithms. These algorithms were designed to move the robot through the desired path in space, and to interact with any sensors connected to the robot. The third level of control was provided at the so-called systems level, wherein commands and capabilities for the application programmer were defined.

In a similar but more important historic development, the NIST developed the "Real Time Control System" (RCS) for the robots they were developing. Sometimes called the Robot Control System, the RCS defined a control system consisting of multiple levels of control operating in parallel and in a hierarchy. In this system each level is connected to two other levels, one above and one below. The only exceptions are at the highest and lowest levels: the output of the lowest level is the input to the actuation system of the robot while the input to the highest level is the task to be performed by the robot system. This system has been the basis for the development of many robotic control systems and remains a significant area of interest at the NIST. DARPA is funding additional refinements and advances to the RCS.

The RCS is often called a task decomposition system because each level of the control system divides a task into subtasks. The level below accepts a subtask from the level above and further refines it into subtasks for the level below it. The process continues until the subtask is a simple elementary move by the robot. This is communicated from the lowest level to the robot. By analogy, consider the general officer who, having developed a campaign strategy, gives orders (subtasks) to subordinate commanders, each of whom in turn defines a set of subtasks (or perhaps objectives) for the officers who report to them. This process of refinement and subdivision continues until the general's orders have been translated down many levels. Finally, each soldier or airman is given a very specific subtask to perform.

The analogy is useful for conveying several concepts about the control system. First, the system uses feedback. Each level must report the status of the subtask to the level above. In RCS feedback, success, failure, or "in progress" reports are normal, with more information provided, where possible. Second, the levels operate in parallel. Just as the general does not go to sleep and await a report when the job is done, so too the various levels of the control system continue to monitor and evaluate the situation. If the situation changes, the orders might change. Every level requires input other than feedback, as well as orders from above. In the RCS this implies information from a world model that carries sensory data analysis, and status. When the situation changes, a command for new or altered action is issued and the original effort halts or is modified.

The general has a global and long range point of view, while the airman or soldier at the bottom has a very narrow perspective. In the RCS, the point of view of each level is different and moves typically from general to specific as one descends the hierarchical structure. The interface to the world model must be able to report the same information in many ways to meet the perspective of the level receiving the data. For an insight into this need, consider the way information is reported to the military officer. The general receives statistics and aggregate data whereas the platoon leader may get detailed information that is quite specific. Note also the occasional need for detailed data on a focused area by the general. This is equally so in the control system of an RCS; the information interface must be multifaceted and flexible.

With regard to time horizons and reaction times, real time at the highest levels might mean hours, while at the lowest level real time is frequently measured in small

fractions of a second. Yet at each level analysis, planning, and monitoring of the level below must be continuous. The time horizon differences thus indicate the complexity of the task at any level as well.

A-1.2 Machine Intelligence

What machine intelligence might be or whether any machine is or might ever be intelligent can be debated endlessly. For the purposes of this report, the computer segment of a robot system controls the robot, and that control is expected to be judged intelligent. Intelligent people do some very stupid things, and just as one tries to minimize those occasions, robot control system builders attempt to minimize the number of "stupid" things the controller forces the robot to do. However, unlike people, robots and their controllers are, in today's state of the art, designed differently for each task. Robots do not learn in the same way that people do. Robots cannot draw analogies. Thus, if you take a robot controller that does a task well, and assign the controller to do a similar task for which it was not designed, it will at best do something stupid. Robots have only the adaptability that is designed into them.

Imagine, for example, a robot housekeeper that disposes of all forms of paper and rubbish on the floor. Imagine it also knows about toys and dolls and knows to put them in the toy box. Without special programming when it was designed, such a robot probably would trash a stack of hundred dollar bills and toss the family baby into the toy box. The technology to tell a robot control system about a generic category such as money has not been developed. This must be kept in mind when considering the capabilities of machine intelligence described below.

Early computers were often called "number crunchers" because they could calculate quickly. Since then computers have begun to manipulate symbols, a slower process than numeric calculation. Because this process requires more speed and memory, symbol manipulation was developed after the development of numeric applications for computers. However, today's computer technology has brought significant development in symbol manipulation; and symbol manipulation is today at the heart of machine intelligence.

A-1.2.1 Reasoning/Inference

Summary: Machine intelligence is founded on inference, the ability to deduce a fact not explicitly stated. By taking advantage of a computer's ability to make an inference, information can be retrieved that was only implicitly stored in its data banks. The machine must have stored both a rule of inference and the data on which to apply the rule. This inference structure is central to machine intelligence: the ability to diagnose a system fault, plan a course of action, or execute an action. From a heuristic point of view, no optimum path through a decision tree of hundreds of rules can be expected, yet a desirable or appropriate solution can be achieved. Rules can be derived from a data base, a knowledge base, or they can be obtained by "learned" experience in operating the system.

Description: Inference, in its simplest form, can be imagined using a data base of father and son relationships. Imagine that the computer knows this rule: X is the grandfather of Y if one can find a Z such that X is the father of Z and Z is the father of Y. A computer with that rule and data base can then be asked to find the grandfather of a

specific person in the data base or all grandfathers. Perhaps the two most pressing research questions in machine intelligence research today are: (1) What is the best search algorithm for finding data that fits a rule? (2) What is the best way to represent information or knowledge? Note that both the rules and the data are knowledge.

The inference mechanism is the backbone of machine intelligence, and can be used to diagnose a system fault, plan a course of action, or execute an action. Consider first the task of diagnosis. Imagine a set of rules that, given a symptom (data point), suggests a discriminating test (request for data). Imagine hundreds of such rules arranged in a decision tree. These rules start with a few general symptoms and end up selecting one of several hundred diagnoses. The diagnoses may also contain a repair action. An example of a trivial beginning sample would be diagnosing a dead radio.

Situation	**Action**	**Result**
No power, Battery operated	Check battery	Battery status
No power, Plugs into wall	Check circuit	Circuit status

In machine intelligence the rules are not written as programs to indicate where to go next. Instead each rule has three parts. Part One is a pattern or situation. When it is matched/true, the rule is active. Part Two is an action to be taken or test to be performed that results in new or different information. After the action of Part Two, the situation or pattern that is not available is Part Three. Part Two is sometimes a request for a test or information, such as temperature of a patient, the results of which will be fed back to the machine. In other cases it is an optional procedure invoked when the rule is applicable; e.g., to locate a target on a targeting computer. The machine starts with some situation and searches all its rules for those that apply. If only one rule applies, it is chosen and the situation is changed. The change is dictated either by Part Two of the rule or by the procedure in Part Three. If more than one rule applies, a heuristic (rule of thumb) is used to decide which rule to use. If that path later leads to failure or is blocked, then the system backtracks to the last point where a choice was made between rules and takes the next alternative. Today almost infinite length back chains are possible, and though it cannot be predicted in advance that a system will be right all the time, in many limited areas the results are impressive. The system knows it has successfully completed a task when the final state matches the goal state.

The above discussion began with a diagnostic example. The machine asked for more and more information to narrow down a diagnosis to determine the cause and potential remedy for the system failure. Similar use of rules can apply to planning and taking action. Consider the identification of a desired goal state. A set of rules can be constructed so that in Part One the pattern identifies some state of the system. Part Two identifies an action that will take the system from the original pattern/state (Part One) to some resultant state (Part Three). In the most naive system, only an original state and a goal state would be known. Consider then the naive approach of determining all the rules that might apply to the original state, and match the pattern in Part One. If more than one rule exists, check for each possibility if the resultant pattern/state matches the goal state. If one matches, establish the action identified in Part Two as the plan and you are done. If none match, choose the first in the list, put the action as the first step in the plan, set the current status to the pattern/state in the third part of the rule chosen and repeat the above. Eventually a goal will be reached, or a block of some kind will occur. If a block occurs, backtrack as described earlier, adjusting the plan to remove steps now eliminated.

It should be clear why this is a naive approach; it might go on forever. The key difference between this example and what is used today is that in choosing a rule a figure of merit is used. That is, heuristic algorithms are used to evaulate the likelihood that the rule will lead to the goal. Instead of choosing the first rule on the list, the rule with the highest probability is chosen. This scheme for choosing how to search is just one of the simplest forms of search strategies being developed. However, the development of a plan can be accomplished by recording the "action" parts of a sequence of rules that transforms the initial location/state into a goal state. This was the point of the above discussion.

Carrying out a plan and formulating a plan is the same for both machine and human intelligence. Unexpected events can disrupt the best laid plans of robots, as well as those of mice and men. To execute a plan, a robot system uses the world model to compare the expected state with the state encountered by the sensory system. When differences occur, replanning takes place to define corrective action. For minor differences, e.g., small positional variances in location of the robot system, a corrective move is made to alter or fix the position and resume the plan. Major differences make the planned steps inoperative; too large a deviation from the pattern in Part One prevents the system from executing the planned action. In this case, failure is often reported with an explanation, so that the level above with greater perspective can replan the action. The nuances in this distinction between a plan that can be repaired and one that must be scrapped are still the subject of research. Today, only the simplest situations can be handled by this method.

A-1.2.2 Sensory Perception

Summary: The sensory system monitors the robot and provides feedback information on the state of the environment and the robot itself. The task of the sensory system is to deal with predictive, incomplete, and conflicting information. Predicting a future state can be achieved only in terms of a carefully formulated model reference of the system and its operation. The obtained data may be excessive, imprecise, or incomplete, yet they must be reduced and interpreted for use by the decision making part of the system. It will be increasingly common to have conflicting data from the sensors resolved into a balanced data set called sensor fusion.

Description: Whatever the task - flying a plane, refueling a truck, loading ammunition, repairing a runway, or firing a weapon - to perform correctly, the robot must know the environment. Recall that each level of a controller provides feedback on the status of a control task to the level above. The sensory system monitors the robot and provides feedback information on the state of the environment. Sometimes that feedback is new information and sometimes it is used as confirmation of location and position. The sensory system must know what to expect. The RCS must be able to predict the state of the environment and feed it to the sensory system to help clarify the data it senses. Sometimes the expectations will concern which direction to look; in other cases it will provide the names of the objects to be sensed, or the sensor values expected.

The task of the sensory system is to deal with predictive, incomplete, and conflicting information. The specifics of these tasks are further described in Section A-2.0, which defines various sensors and sensor tasks. This discussion is confined to the sensory task from the point of view of machine intelligence.

A-1.3 Software Systems

Robot systems pose all the current challenges known to computer science. This application domain must operate across multiple heterogeneous computer systems in a distributed and parallel fashion. Robot systems must contain sophisticated data bases and world models that are updated in real time from several sources while they continue to be used for mission-oriented performance. These systems must communicate with the outside world using all kinds of sensors, image analysis, and complex graphical interaction, and must use the latest AI and knowledge engineering techniques. Robot systems must be made reliable and fail safe because they will operate weapons and be in the first line of defense for the nation. These systems are stretching the state of the art in software and they make excellent testbeds for the new developments.

There are two kinds of software: (1) applications software, which is the human interface for people who develop robotic applications (discussed in Section A-4.0), and (2) systems software, which is the architecture of robotic control systems. Systems software is discussed below.

A-1.3.1 Object-Oriented Systems

Summary: In traditional software systems, programs are active but the software itself is passive. The range of tasks that might face a robot system suggests that the software be actively adaptable. Object-oriented data systems are just a first step in reaching this level of flexibility. The new type of data will require new object or task language systems.

Description: Object-oriented programming is a recent innovation in computer science. The key new concept is active and self-describing data. In traditional software, programs carried out instructions to perform tasks; the software merely held data in some organizational form. This led to a situation where data file structures and organizations could be interpreted only by the programs that wrote them. In closed-end applications, in which the program and data reside on the same machine for a fixed and well defined task, traditional organization was adequate. But in the new world of distributed computing, networks, and evolving uses for data, the traditional access method breaks down. Consider a robot that gathered data for a specific purpose. Now, under new circumstances, it must use that data for another purpose. Suppose fire control data acquired for targeting is now needed for navigation. If the fire control program and navigation program reside on different computers and use different data formats, we would be in the position of having the data but no way of referencing it. Imagine how difficult it would be to know who would read all the data in the world model under all possible circumstances. Since such a situation is unfortunate if not intolerable in a robot system and in most other modern applications, a method for active and self-describing data is being developed. Object-oriented data systems are just the first step in carrying these principles to fruition and are very important to the future of complex robot systems.

Clearly the new type of data will require new languages and methods of connecting software modules. Object or task language systems that are now being developed provide the first steps in the directions described above.

A-1.3.2 Intelligent Data Systems

Summary: The principal objective is to accurately document all essential characteristics of the operating environment of the robot in a "world model." These types of data are becoming more available in terrain maps, nuclear plant models, and chemical plant models. A related issue is the integration of multiple data bases into a single distributed information system (the retrieval, updating, and deletion of required data).

Description: It is important in the computer science research community to discuss a world model and the functions and data for which it is responsible. Yet the general principles on which to base the development of a world model are not well understood. Important questions of data organization and representation remain open research questions. Architectural issues with respect to world models stored across multiple computers also remain viable research agendas. Consider the variants on blackboard systems for common memory.

A related yet separate issue is the organization and retrieval of the data in a world model. Much work is under way to integrate multiple data bases into a single distributed information system. This work clearly applies to the development of robotic world models. The research on integrating AI question answering and planning techniques with traditional data base retrieval systems is also important. The massive efforts needed to provide a way to organize data from multiple sources and to combine these data with AI techniques still lie before us.

A-1.3.3 Software

Summary: Software is the basis for decision making within the robot structure. It must be fast, reliable, redundant, fault tolerant, modular, and layered. Software cannot be developed independently of the operating system on which it is to run. Testing and qualification are also emerging as a major issue.

Description: It has been assumed that a robot system will be built on a set of multiple computers. These computers, probably heterogeneous, would be organized to distribute the computing load across both hierarchical layers, and heterarchical peer computers. It is further assumed that various modules and subsystems will be developed independently of each other and at various times during the duty cycle of the robotic controller system. Finally, in the case of faulty systems or damage to the controller, it is assumed that redundant elements and a degradation architecture will allow the robot system to maintain its function or degrade gracefully. When dealing with a component failure, this is more desirable than precipitous failure of the entire system.

For all but the most trivial versions, many challenges must be faced to incorporate these characteristics into a robot system. There is no general architecture or set of guidelines to follow. Still, fly-by-wire systems, weapons of various types, and many space applications are deployed and their software systems have many of the attributes defined above. Thus, the challenge is to provide a systematic and general environment for the production of a system with the desired characteristics.

The speed of execution and complexity of the architecture define new challenges to the software development environment. Research in the development of parallel computing systems, microprocessor development systems, and network and communications

systems are being brought together with the new software and data environments to tackle these problems.

Robot system software reliability is linked to the performance of the underlying hardware, so this issue is discussed in the section on hardware. There remains then the question of software reliability. Research in this area has been hampered by the lack of formal models for software and its development. Proving software correct and a formal means of testing software remain important open research issues.

Software reliability is further compounded by the research into the automatic generation of software, which is now taking place. Automatic generation efforts are in their early stages. It is too early to know the impact on software reliability, or on robot systems in general.

A-1.4 Computer Architecture

Summary: The pervasive need (and benchmarking) for speed in computation is driving computer architecture development today. Only recently have valid new architectures (multiple processors) become available. It is predicted that in 1989 a 32-bit processor architecture (each capable of 50 MIPS) will become available. This massive development will have an enormous impact not only on robot operation but also on robot design.

Description: The hardware systems on which robotic computations take place have been evolving rapidly. The large scale computers of the 1960s have given way to more powerful desktop computers in the 1980s. The cost per computation decreases every year, while the number of computations per second grows almost exponentially. Today, personal supercomputers and computer-based microchips can control any device we might deploy. Consider the number of microcomputers that are already used in automobile and home electronic systems.

Robot systems use large numbers of computers distributed throughout the robotic structure. Computers augment the control of various autonomous functions and connect the components through computer communication to the robotic control function. Even simple robot arms used in manufacturing have a microcomputer at each joint. Microcomputers are also part of each sensor and the sensor control system. All this is in addition to the computers needed in the hierarchical-layered control.

Computers are not a single device, nor are they all alike. One finds multiple chip architectures designed to enhance particular aspects of the computational task. Special computer chips are being designed for emission control circuits on cars (these differ in the internal architecture from the chips designed for rapid symbol manipulation) and as onboard processors in a pressure sensor. Architectural trade offs at this level balance speed with accuracy, input/output capability with instruction set and memory addressability with word size. In other words, robot systems are becoming complex. They require computer chips with the above capabilities and additional design features to meet specialized and evolving needs in different parts of the system. Thus, the architectural needs for robot systems vary with the computational task and location of the chip in the robot architecture. In fact, the need for accuracy, reliability, and special operating conditions in robotic applications is expected to require special computer architectural designs because the speed and memory capacity of today's robots generally do not allow additional tasks, such as control of dexterous end effectors, processing of vision data or

addition of AI-based programs. In particular, the control of dexterous end effectors may require a complex additional computer. In some cases, new designs will tax the state of the art of computer architecture for some time.

The above discussion, which focused on the computer architecture of a single chip, trade offs, and requirements expected for robot systems, define the intra-chip requirements. In addition to the intra-chip requirements, consideration must be given to the need for high speed computation on massive amounts of data and the integration of multiple computers into a higher order control system. Multiple coordinated manipulators will be needed in ordnance disposal, space vehicle retrieval and servicing, and remote automated assembly in hazardous environments. These systems will require attention to the inter-chip architecture. In addition, the speed needed for computations required in future robot systems will stretch the limits of single chip architectures. These speeds may be achieved only by using chip sets in a parallel architecture.

Inter-chip architecture will play a critical role in the advancement of complex robotic applications. Future systems may use many sensors generating a large information array of roughly equal significance to the system. This reality of excess data, all at the same level, has been adequately demonstrated for machine vision. It is much less well understood with regard to the real time operation of the dynamic model of the manipulator system. Six distinct computational levels must be implemented serially. In each of these levels 100 to 800 distinct functions can be calculated in parallel. Parallel processing is therefore essential for the real-time control of any system having the geometric complexity of a general robotic manipulator. An economical parallel processing architecture for spatial end-effector position sensing would be a breakthrough for the next generation robot.

The additional requirement for integration capability goes well beyond the need for communication, which is in itself a challenge. Shared memory and common bus structures are vital to the real-time coordination required by the control systems architecture. The more computers, the less feasible are traditional implementation schemes. Thus an inter-chip architecture that supports the concepts of coordination and integration of multiple cooperating processes is a key to the future of complex robots.

The exact parallel architecture most suitable for robot control is unclear. While a completely general multiple instruction multiple data (MIMD) architecture, tightly coupled with shared and distributed memory may be desirable, a less flexible but also less costly single instruction multiple data (SIMD) architecture may be suitable in some applications. The decreasing cost of computer hardware and increasing availability of commercial parallel processors make this an ideal area for investigation.

A-1.5 Sophisticated Communications

Summary: Communication mismatches will plague robot system integrators until the development and acceptance of appropriate standards. Complex robotic applications will be expected to integrate and organize information from hundreds of computational sources. However, communication technology is evolving rapidly to meet the needs for greater speed and capacity in communication channels, making standardization elusive. Reliability and redundancy are critical design factors for robot systems that will operate remotely or in battle. Communications issues span tightly and loosely coupled systems, grow more challenging with increased complexity and multiplicity of computers in the

robot system, and are even more challenging in the military arena of hazardous environments, remote operation, and the critical requirement for functionality without breakdown.

Description: Communications among systems that are not part of the same chip set and were obtained or designed as separate components require very high speed special "BUS" or backplane architectures. The limitation in this type of interconnection then becomes the number of distinct processors that can be hooked to or share the communications channel. Work is progressing in setting up multiple interconnected high speed channels, but proximity in the physical sense is also a limiting factor.

Complex near and long term robotic applications will be expected to integrate and organize information from hundreds of computational sources. Attention must be focused not only on the physical interconnections and the "path" for communications, but also on the implications of the volume of information versus capacity, criticality, and timing needs for various messages. Research into the organizational and media issues is well under way in all of the network communication and telecommunications centers recently established. However, research on the scheduling of information, prioritization of messages in a heterogeneous network, and the concepts of information instrumentation remain largely unexplored. These become even more important as one considers the impact of hostile environments on the network, as well as the need for secure communications and encryption.

In summary, the communications issues span tightly and loosely coupled systems. These issues become more challenging with the increased complexity and multiplicity of computers in the robot system, and in the military arena of hazardous environments, remote operation, and criticality of functionality without breakdown, the challenge is enormous.

A-2.0 Sensor System

In the simplest form, a sensor system is a set of shaft encoders that provide position data to a simple controller. More complex are multiple three-dimensional sensory systems. These systems provide several image spectra, along with a host of inward and outward looking sensor systems. Imagine all the data fed to a fly-by-wire system, coupled with weapons sighting systems, which provide "data" to the computer control system. The type of data required and the difficulty of converting it from data as sensed (large amounts of data) into digested and usable data for the control system, is a function of the complexity of the task to be performed and the robot itself. For example, the task of the sensory system is to tell the control where the components of the robot are. The sensory system also senses change in the environment, a task that can grow to be infinitely complex based on the task and the environment. The sensory system's requirements are vastly different for a stationary robot welding car bodies in a factory than a mobile battlefield robot that is refueling trucks, or unloading ammunition in a war zone.

Sensor systems are a collection of individual sensors and their transducers. An important issue in sensor systems is the resolution of data reported by two or more sensors. This is handled in some form by the sensory part of the control system. However, aspects of the data-in-conflict problem arise in a specific sensor when a prediction has been made regarding what is expected. This prediction capability will be

the norm in the future as robotic applications and their controllers grow more sophisticated. In this environment a sensor is told what to expect based on the other factors known to the control system. When the unexpected happens, the robot should not respond as though the expected was encountered, for then we would not need the sensor. In fact, the sensor is most valuable when the unexpected occurs. Thus a dimension of the data-in-conflict situation occurs in resolving the data seen by a single sensor and the expectation set up by a prediction. This problem is crucial in avoiding the self-fulfilling prophecy delusions that can be potentially disastrous for the robotic control system.

A second generic sensory problem deals with providing increased resolution and performance specifications across sensor types. Robotic applications can grow so fast that sensor accuracy, reliability, and resolution will always be limited.

The final generic problem is the interface. In the absence of a well-defined interface specification, robots and sensor systems will not be easily modularized. Both a data and mechanical interface specification are needed. In addition, contextual information on the sensor and its capabilities are needed so that sensors can be readily added or removed from the sensory hierarchy.

A-2.1 Force and Positional Sensing

Summary: Increasingly, the robotics community is relying on low level sensing (position errors measured through vision, range finders, capacitance, and acoustics). What is really needed are higher levels of information (force, velocities, accelerations, and jerks) that are higher order properties in the model reference. When these elements are integrated (in real time), they can be used to predict the condition of the system at the lower level and therefore compensate for it directly through feedforward commands to the control system. Sensor fusion at this higher level can occur only if the model (or plant description) is available at that level in real time.

Description: Force and position are the basic sensing parameters for feedback to the robot control system. In some cases the feedback can be provided to an operator, but usually it is connected to the sensory portion of the machine intelligence system on a robot operating in an unstructured task regime. Force sensors deserve special attention because they are indispensable in man-machine communication and enhanced machine intelligence. Integrated strain gauge elements and piezo-resistive films can be deposited directly on compliant structural elements to generate signals to be interpreted by local VLSI electronics. The scale of such devices must match the scale of the task spectrum of the robot. Industrial robots involve force levels of five to 150 lbs. and must provide high reliability with minimum compliance. For miniaturized systems, a range of a few ounces and a relatively higher compliance would be acceptable. Few such devices are used today.

Tactile sensors are a special type of force sensor that give the robot a sense of touch. In tactile sensing three-dimensional space can be explored to determine properties of the robot environment. Tactile sensing is a transduction process in which the features of an object are converted into signals. In some applications, mechanical tactile sensing has more capability than human sensing.

Positional sensors can vary physically with the task and robot system. However, they are always designed to give the robot information about its location in the environment or the world. A robot is a collection of joints or motion systems such that each joint has a position encoder that provides feedback on its position or location. In some cases the feedback is relative while in others it provides an exact or absolute location. Angular resolution of joint position encoders of 20 to 21 bits (one part in a million or one arc second) is feasible but at the expense of high cost ($10,000 for the encoder) and size. Some industrial applications would warrant this resolution when specified end effector accuracy approaches 0.001 inch. Force sensors of 50 lbs. maximum load and one ounce resolution have been developed and are being marketed for approximately $3,000 to $8,000. In themselves, neither of these systems is sufficient to accurately locate the end effector in world coordinates. Accurate data on the spatial location of the end effector (and the rest of the robot as well), without using sensors attached to the robot structure (which introduces deformation errors, noise, and great complexity), remains essentially impossible today.

One solution to the onboard sensor problem is to use area-mounted sensors independent of the motion of the robot system. This is less practical in an unconstrained environment, but can work well elsewhere. The idea is to mount a sensor near the robot. The sensor looks at parts of the robot, which it can locate very accurately. One such sensor is called a range finder, which determines the distance to a point on the robot. Laser range finders have become popular lately and are used on many robots. Some laser range sensors have resolutions of one part in 1,000. The resolution of the laser range finder is enhanced by mounting retro-reflectors on the robot at the desired location, perhaps the end effector. The techniques of optical triangulation, structured light, and laser interferometry have been used in such systems. However, line of sight (between the sensor and robot) and high speed computational capability for data reduction are essential elements of this type of sensory system. When independent sensors are not available, the positional accuracy of the robot system in world coordinates is not always able to provide adequate compensation for target deviation. A solution to this problem would be a breakthrough in robot system control and would facilitate a much broader range of useful applications.

A-2.2 Imaging Sensors

Summary: An imaging sensor captures an array of data. Each location in the array represents an individual sensor value. Each value in the array of a TV image might represent a gray scale value representing the light reflected toward the camera. The receiving signal may be temperature, radiation, sonar, force (tactile), and potential fields (magnetism). Image processing can be divided into two forms: low level without scene knowledge and high level, which benefits from advanced knowledge of the scene. This processing requires specialized computer hardware and software. This is an intensive field of activity at the present time.

Description: Imaging sensors are not restricted solely to the visible spectra or TV cameras. A laser range finder can capture a depth image so that each element in the array represents the distance along a path normal to the sensor to the object in the field of "view." Various forms of spectral image cameras, including visual and infrared, are in use. Also, various range images are routinely acquired with laser range finders and acoustic systems.

For robot systems of the future, any system that can produce an image is a candidate sensor. One can imagine medical robots using x-ray and nuclear medicine scanners to produce images. One also conjures up the routine array of sonar, radar, and other forms of military sensors that produce image data.

The physics of each sensor is independent, and at the final stage of processing or interpreting the image sensor data, one wants to use the knowledge of which type of sensor collected the data. Yet, even given these two factors, a number of common procedures and problems can be described generically.

The resolution of the sensor image varies with the sensor type. For many systems resolution is a function of the lens or imaging system. While there is no fixed relationship between the resolution and the size of the image in the computer that processes the data, greater resolution means larger images. There are, however, significant speed-of-computation issues raised as image size grows. In a TV sensor, using standard TV cameras or those modified for digital conversion and automation, an image is generated that is on the order of 256 x 256 pixels or 512 x 512 pixels, or some combination of these (depending on the type of camera and application). Special purpose camera digitizing systems are available at array sizes of 1,000 x 1,000 and small multiples of this up to about 4,000 x 4,000. At the high end of this scale the time to perform even simple image operations becomes significant.

Image processing can be divided generically into two forms: low level processing, done without information about the expected scene, and high level processing, which takes into account the expected scene and transducer characteristics. For the most part, low level image processing is common to many sensors, and we describe some of these capabilities below. In addition to the processing images for computer analysis, low level image processing is often used to ease the burden of human interpretation. In a robot this might be a precursor to presenting the sensory data to a human for analysis. Low level image processing frequently includes histogram modification: contrast stretching of various forms, noise suppression or smoothing, image sharpening operations, and a variety of effects that enhance details hard to see in the original image.

Low level image processing, when used as a precursor for machine analysis, also deals with noise elimination. It does not deal with contrast stretching or visual improvements because the data in such operations compensate only for the functioning of the human visual system. As such it occasionally discards useful data from the machine analysis perspective. For machine analysis purposes, the low level vision processing is used to identify edges, lines, vertices, regions, geometric faces, and other basic elements of an image. Low level images are often processed with hardware specifically designed for image analysis. Higher level image processing is done with the guidance of the sensory perception module. However, in other less sophisticated applications the low level processing continues with such information. Classical capabilities in this latter area are routinely used to verify or identify objects in an image, to locate an object in an image and transform its location to robotic coordinates, and to perform simple inspection tasks. The image processing task is frequently time consuming on traditional computers due to the volume of data and the type of operation involved. Thus, special purpose chips commonly are available for low level vision applications and are now being designed for high level processing.

How do we deal with many samples over time? In image processing systems, time is important for tasks that involve motion. Simple subtraction of images provides crude

motion detection, and derivatives over time are a rich domain for analysis. Many systems can handle multiple images. They can mix spatial features (found in one image) with time domain features to provide for more powerful analysis. Time manipulation in image analysis is one of the simplest uses of knowledge-based image processing or high level analysis. Consider the example of a structured light stripe system that captures two images, one just before the flash (stripes) is projected and one during the flash. By subtracting the image known to be taken without the flash from the flash image, one gets an image with only flash data for analysis. Structured light systems, multiple camera (stereo and other forms), and multi-spectral images are processed in ways that use information about how the images were acquired in order to interpret or clarify them. Frequently, so-called three-dimensional image systems combine a range image with a visible spectra image. They also might analyze a stereo pair or structured light (known geometrical decomposition) to obtain the dimensional measurements in three dimensions.

High level image processing, on the other hand, uses information about the sensor system and the underlying image known *a priori*. A layered set of higher level sensory processing steps make up the sensory hierarchy described elsewhere. The discussion here is confined only to the first level of context-based processing.

Much research is under way to determine how to best use *a priori* knowledge and probabilistic data. It is not surprising that when probabilistic data are available (a certain object is expected to be in the image) there is uncertainty how best to use it. Current research is following the lines of using knowledge to guide the processing and as a weight in resolving ambiguity in image processing decisions.

Consider, for example, the task of finding all four corners of a rectangle expected to be in an image. If it is known that it is a rectangle, the corner locations can be adjusted to line up. That is, a selection can be made from among several candidate locations for each corner provided by a low level algorithm with the knowledge that the four corners are interrelated. The danger, of course, is when a rectangle is expected to be seen and for some reason a circle is seen instead. The temptation to see the circle as a rectangle because that is what is expected, must be avoided. This research area is the key challenge.

Knowledge is used in other ways too, such as to eliminate noise, or to use the results of image elements to sharpen the elements of an adjacent image. This latter technique is sometimes called relaxation because decision criteria can be relaxed. An example would be the decision of whether or not a particular image point is a vertical edge point. If one knows that the image point directly above and directly below were decided to be vertical edge points, one can relax the criterion at the point in doubt. Again, of course, there is the possibility of error, and this continues to drive such research.

A-2.3 Image and Speech Understanding Systems

Summary: Significant breakthroughs in understanding software will be required before a robot can be provided with capabilities even remotely matching those of a human in general adaptability and applicability. The needed breakthroughs are centered in the field of AI. Thus, representation, memory size, and speed-of-search are all obstacles to current systemic capabilities. Presently, the machine vision being used in factory

inspections and speech recognition systems is increasingly useful for man-machine interfaces.

Description: As image and speech understanding systems improve, they will play an increasingly important part in robot systems. They are frequently discussed as sensory systems because of the underlying need for image or sound transducers, but the real research efforts in these fields is not in the transducers or low level data analysis, but in the sophisticated use of knowledge to reason in the appropriate domain (image or speech. Research in these areas has been heavily funded for many years and significant capabilities exist in both domains. However, both domains require significant breakthroughs before a robot can be provided with capabilities even remotely matching those of a human in general applicability and adaptability. These are both AI problems and progress is limited by general problems in AI. Thus, representation, memory size, and speed-of-search algorithms are all obstacles to current systemic capabilities.

These systems, however, can provide an impressive array of capabilities under various constraints, and are actively used in commercial systems today. Even so, they remain a vital area for research, and are beyond the scope of this taxonomy. No attempt is made to detail the required research beyond the general statements of increased capability in less controlled environments.

A-2.4 Other Sensors

Summary: In the future, an excess of sensor information is almost certain. These data must be reduced to a minimal number of key requirements for system response. Today robots are highly deterministic except when responding to global process requirements. Future mechanical architectures must be designed to absorb the reduced commands obtained from a broad range of sensors. If not, then advances in sensor technology will have no outlet. This includes the concept of adaptive control, and also means that the geometric character (distributed degrees of freedom at several scales) of the structure must match the hierarchical nature of the sensor system.

Description: The purpose of the sensory system is to sense the location of the robot systems' components in space (on and above the Earth) and to gather data on the environment. As the robot evolves from the one-armed factory system to military vehicles and systems, it needs more sophisticated sensors. In addition to military applications, olfactory and taste sensors are needed to complement the other human-like senses provided for in robotics by tactile, visual, and acoustic sensors. Research in these areas is continuing in various stages as needs for them on robot systems arise. Fire detection robots, for example, have smoke sensors. Some robots that operate in chemical environments can "taste" a mixture or brew. Although demand for these senses is still small, one can imagine various robotic scenarios of the near future that would require some of them on a sentry robot or a safety-monitoring robot in space.

New sensors will arise from previously instrumented, non-robotic systems that now have autonomous or semi-autonomous control systems. Consider, for example, all the sensors in a fly-by-wire airplane, or an automatic targeting weapon system, or any command and control system that is now being equipped for robotics. In these cases the emphasis is not on developing the sensors, but in interfacing the sensors to a robotic system in a way that they can be used effectively.

Robots use sensor systems in many ways and with many levels of complexity. Integrating the sensors from existing systems will require research into standards and procedures that allow for optimal or near optimal control by the robot system which is equal to or better than the non-robotic version.

A-3.0 Actuation Systems

The actuation system here implies the mechanical structure, including prime movers, links, and bearings, which is capable of performing physical tasks. Usually, this system is thought of as a manipulator. It may have only one degree of freedom (DOF), or it may have 20 DOF. It may be serial (one link, one joint, and one link), it may be parallel (like a legged platform with several identical legs), or it may be a hybrid of these. The main objective of the actuation system is to accurately transform a computer command signal into a physical operation, such as a motion, a force, or any combination of motion and force.

A-3.1 Structural Geometry

Summary: An architectural issue is the balance of serial and parallel mechanical structures. Almost every existing robot is serial. Yet precision control in biological systems are almost always parallel (the extraordinary precision of the motion of the human eye). The Stewart platform (represented by the Link trainer for pilots) is one of our simplest parallel systems, and it has attributes completely different (load capacity, stiffness, and distributed error instead of accumulated error) from serial structures (high dexterity, simple assembly, and compactness). What is needed is a set of architectural rules that allow the designer the best mix of serial and parallel structures for 3, 6, 12 DOF systems, and beyond, depending on the intended system application range.

One of the most demanding operational tasks faced by the robotics community is the precision interaction of two (or more) similar (or dissimilar) arms. Walking machines can be made up of 2, 3, 4, or more interacting legs. Hands with multiple fingers are being considered. In repair operations (especially in space and in microsurgery) there will be the need for dual arm operation (6 DOF each). Basically, the system represents an excess of inputs (say five) from a total 12 DOF, which allows for a precision one DOF interaction between the end effectors. All operational criteria must now be satisfied by internally balancing a total of 12 inputs against seven independent outputs. This balance has to occur in real time and essentially means optimization in 30 milliseconds. Many classical optimization problems of this magnitude take hours of computer time. Yet a strategy must be developed to meet this operational need or dual arm systems will not be able to perform many functions for which they are now being considered.

Description: The analytical tools for the design and operation of the geometry of robot arms are among the most complex problems in robotics. The cartesian robot contains no fixed dimensional parameters. Today, many dexterous arms (similar in proportion to the human arm) contain two fixed dimensions. The most general six-DOF arm would contain 18 design parameters, all of which should be evaluated to enhance the potential reach, dexterity, and obstacle avoidance of robot arms. Recently, researchers have shown that the complex mathematical control equations may fail frequently and cause disconcerting disruption in the smooth or precise operation of the arm. Future arms will be a balance

among the number of degrees of freedom (redundancy of two to make an eight-DOF arm) and the level of complexity in the geometry and the associated planning and control algorithms. Most arms are now serial devices (one link, one, joint, and one link). Future geometry will involve the study of parallel structures for enhanced precision and load capacity. These devices could become very small (miniature manipulators), demanding more from analytical theory and design methodology. Finally, two or more robots could cooperate on an assembly task, such as welding. In this case, what is their common workspace, dexerity, and operating region without mathematical uncertainties or special locking configurations? What is the desirable balance of complexity among the interacting arms?

Two dominant issues will affect the design geometry of robots for space operations. Space robots will have to be very lightweight yet have the ability to operate in the micro-g gravity field. Applications, such as light machining, will require powerful but precise end effectors. Yet the crowded environment of compact laboratory modules will require greater dexterity than that of current industrial robots. This leads to the question of serial geometry (for high dexterity to perform complex tasks among obstacles) versus parallel geometry (for precision and low weight).

Part of the solution may come from modular robot structures, configured on demand to meet the dexterity requirements of a given range of tasks. When precision is top priority, disturbance rejection can be achieved by making the structure "electronically rigid." This precision can best be achieved by using a new mechanical architecture of layered large and small prime movers combined with similarly scaled control technologies (which may be called control-in-the-small). To achieve this level of technology, the complete dynamic model of the system must be calculated in real time, a requirement no industrial robot has met.

The manual controller to be used by men in space will have to be geometrically optimized for best match to the human operator and universal in that one geometry is capable of driving any "slave" robot. Docking mechanisms will require special geometries that are highly parallel, dynamically responsive, and rigid though lightweight. Because of the micro-g gravity field, many operations will require two arms operating on the same object; i.e., 12 actuators working to control six to eight output motions (a redundancy of four to six input parameters). This problem is quite complex and is now being formulated in research laboratories.

A similar problem involves a snake robot with a series of two- and three-DOF modules to create highly dexterous systems of eight or more DOF. A more complex problem involves the motion of walking machines (a proposed mobility platform for the space station). Four actuators in each of six legs would require 24 inputs to control six outputs (a redundancy of 18). The solution combines modern control theory, AI, structural dynamics, and analytical geometry all operating in real time (less than 30 milliseconds).

A-3.2 Structural Dynamics

Summary: A dynamic model of the robot is needed to complete its control system. This means that the complete dynamic description must be obtained in less than 30 milliseconds and preferably five milliseconds. This is increasingly possible on pipeline processors (approximate cost today $20,000) and should be available at a far lower cost

30 years from now. The central concept of model referencing and feedforward control (the opposite of feedback control) soon will be feasible. Feedback cannot be expected to operate increasingly more complex systems that are highly nonlinear and coupled. Hence, sensor feedback need be used only to correct the inaccuracies of the feedforward model and the unmeasured disturbances in the unit process faced by the system.

Off-line programming implies a complete numerical awareness of the machine system including all geometrical, mass, control, temperature, drift, and deformation parameters. Otherwise, the computer cannot drive the system except to meet the simplest of functions (of low value). Without computer control, access to the data base is lost and the factory of the future fails. Off-line programming also implies a level of metrology virtually unrecognized by the community. This metrology eventually will have to be available at the work site to identify new parameters introduced by repairs, "tech mod," or software changes. In the meantime, careful laboratory development of robot metrology is essential to fully characterize the state of the art and project R&D requirements into the future.

Description: Today most industrial manipulator arms are very flexible and easily deform under load (from 0.1" to 0.2"). They respond to simple handshaking at frequencies less than 10 cycles per second (cps) which means that their fastest cyclic speed would be no better than 30 revolutions per minute (rpm) (compare with most packaging machinery at 300 rpm and some textile machines at 3,000 rpm). The associated deformation may be caused by dynamics of the system (usually known) or may originate in the task (routing, force fit assembly, and deburring), usually unknown.

Many of these future applications of robotic manipulators will require a high level of precision under large load variations. Today all manipulator systems operate open loop in which there is no accounting for either the dynamics or the external loads. The barrier to meeting this fundamental objective is the ability to create the model in real time (say about 30 Hz). Having the model in real time would enable the compensation for the system deformations and predicted improvement of precision under load by a factor of 10. As this technology becomes available, more robust control strategy will be implemented to allow lighter weight structures (especially desirable in serial arms). As dynamic control is improved, redundant DOF will be used to enhance controllability.

Alternatively, if parallel structures are used, dynamic modeling could be made more accessible to real-time operation. Associated with these activities is the dynamic programming of the end effector motion to reduce command shock induced oscillations. This objective is closely related to the desire for high speed "slewing and touching" in minimum time.

None of this activity can proceed until the parameters for the link masses, link deformations, and actuator control circuit parameters are accurately identified. As many as 130 parameters are involved. Hence, development of design tools and criteria for these lighter and faster arms will be essential.

Because of the special constraint of minimum weight for space operations, a full fly-by-wire approach to the dynamic operation of robot systems for the space station will have to be developed. In some cases, massive inertia loads will be involved - the 55-ft. long robot manipulator system in the shuttle could be used with a smaller robot to form a "cherry picker" configuration. Because of the large scale of these systems, dynamic collision avoidance procedures must be imbedded in the operating software. Also, robot

structures may need to operate in an acceleration field during docking maneuvers. This field creates a very complex inertia load distribution that has to be dealt with by real-time dynamic modeling and adaptive control techniques to ensure that the required docking forces and berthing dynamics are being maintained. On a smaller scale, many unit processes during assembly and maintenance will involve light machining tasks that generate large force disturbances. The overall goal to create a minimum weight robot requires flexible links and actuators with marginal load capacities.

These requirements put an exceptional demand on the operational control software that must be used to compensate for these limitations. The operational software can be established only by maintaining an inclusive dynamic model of the robot structure (i.e., the fly-by-wire concept now used in the control of modern fighter aircraft). This software must work in real time (less than 30 milliseconds). This has been done for 15 DOF systems of completely general geometry and mass content. Given the dynamic model, it is possible to maintain a given end effector force, a desired level of dynamic response, or to compensate for deformations due to force disturbances.

Achieving these goals is complicated when extra DOF, such as in a snake robot, are used to provide additional dexterity. A combination of graphics (computer-aided design or CAD) and control based on the dynamic model and AI for internal decision making will be required to run these redundant systems. The walking (or crawling) system is probably the most complex system to dynamically control. Internal dynamic forces (at each of up to 24 input actuators) must be balanced to create six desired output forces acting on the body of the walking machine. Were the body also to carry a robot manipulator to act on its surroundings, a much higher level of dynamic modeling and control would be required.

A-3.3 Actuation Mechanisms

Summary: The driver of the mechanical system is the prime mover (electrical, pneumatic, or hydraulic). This prime mover is increasingly sophisticated electric servo motors. Some of these are direct drive without gear reduction. Virtually no work has been done in recent years on lightweight, stiff gear reduction mechanisms. Another question just emerging involves the number and distribution of actuators within the mechanical structure.

Description: Electric prime movers are increasingly common. Because of their inherently low load capacity, they almost always require mechanical force amplifiers such as gear trains or metal tapes. These amplifiers add weight, compliance, and backlash, and they increase maintenance and reduce reliability. Hydraulic prime movers, although powerful, have limitations such as fluid leakage (a problem in some clean room operations), sensitivity to dirt in the fluid passing through delicate servo-valves, stiction, and variable bulk modulus in the fluid circuit. Pneumatic actuators are inordinately "soft" and very difficult to control for precision positioning under load. New electric prime movers (based on rare earth materials) are appearing that have greater load capacity and lower weight. Amorphous materials (powder metallurgy) may significantly reduce hysteresis losses having the same effect. Better control through the power of DC motors based on V-MOS technology and hybrid implementation of digital and analog designs should provide enhanced load capacity, dynamic response, and resolution. Antagonistic impulse control circuits may soon be developed with "crossfiring" to further improve positional resolution.

Miniaturized prime movers are among the critical unmet needs required to drive improved robot hands or micro-manipulators suitable for microsurgery, microassembly, and small scale inspection and maintenance. At this scale, friction rapidly degrades positional resolution. The load capacity of the arm depends mainly on the size of the arm's actuators. Generally, about 90 percent of the arm's deformation occurs at the actuator. Light duty arms today are designed to carry 10 lbs. Infrequently, arms are designed to carry 200 lbs., but they are heavy, imprecise, sluggish, and certainly not portable. A load capacity of 200 lbs. is recommended for steam generator maintenance in nuclear reactors. In microsurgery, load capacity may be measured in ounces. One of the best ways to improve load capacity is to place the actuators in a parallel structure so that they can be carried by the base and not by the arm as they now are for serial manipulators.

Another useful research effort would be to seek an optimal distribution of actuator sizes in a given arm geometry. Modularity of the prime mover and its surrounding physical structure would provide a major opportunity to reduce the six to seven year design-to-market cycle time now required for new generations of robotic manipulators. These modules (or building blocks) would be a seires of 1, 2, or 3 DOF units that could be assembled rapidly by a designer to respond to the requirements of a given application. Such modularity would greatly increase the breadth and rapid diffusion of robot systems.

Most actuators now used in manipulators are off-the-shelf prime movers not specifically designed for precision control of large coupled motions of robots. This approach does not lead to an optimum balance between the best characteristics of the prime mover and the physical structure of the system. Today many actuators are too heavy, have poor resolution and response times to commands, generate backlash inaccuracies, are not stiff under load, and do not contain any local intelligence. The next generation of robots must be constructed from a large class of near optimum actuator modules, and must be rapidly scaled (small and large sizes) with standard physical and software interfaces for effortless assembly. Enhanced maintenance due to this modular design is an obvious benefit. This approach is the primary reason that the application of the modular microchip is so widespread.

A manufacturer recently announced a three-DOF hydraulic wrist. Cincinnati Milacron has aggressively implemented their three-roll wrist. A Japanese painting robot uses a sophisticated linkage-based three-DOF wrist of high dexterity. The human system is composed of a three-DOF shoulder, a two-DOF ankle, a three-DOF wrist and forearm, a two-DOF knuckle, and a three-DOF hip. These systems are capable of high positional resolution because of muscular antagonism, which eliminates backlash. Friction at very small scales can be reduced by using anti-friction ceramic bearings. Parallel linkage structure can be used in the module to create very high stiffness with low weight. Hence, it can be argued that the next generation of robot system will come a great deal sooner if a major thrust for structural modules is pursued.

A-3.4 Manipulator Systems

Summary: It is increasingly possible to create several layers of control (0.1 percent, 1 percent, 99 percent) within the same mechanical system with separate task responsibilities associated with each level. The large scale (99 percent) would take on the global motion objectives now found in most robots (which are geometrically extremely simple). The next layer down (1 percent) might take care of deformations in the system due to forces

in the process work function. The next layer down (0.1 percent) might take care of small changes due to temperature or electronic drift. This kind of layered architecture is very similar to that used to build up software systems. Hence, matching these hierarchical needs both in software and hardware is not only essential but necessary for future cost effective robot systems. This layering is what is meant by making the system more responsive to sensor-based commands.

The modularity of personal computers is now an accepted and the necessary reality of computer architecture. PCs are layered with nearly standardized interfaces and control software. Such modularity in robotics has been pursued only in the most elementary sense. A true architecture, where local priorities, scaling issues, and subsystem integration are all involved, has yet to be addressed. Such modularity and architecture is essential for the growth of the mechanical technologies, especially if their costs are to become competitive. This class of architecture allows a continuous evolution of the system while preventing obsolescence by making "tech mods" feasible at the modular level without disturbing the system.

Ultimately, the success of an aggressive technology for robotics will depend on the ability to design the system to meet a broad range of operational requirements in terms of an excess of 100 or more available system parameters (for a 6-DOF serial arm there would be 18 geometric, 42 mass, 36 deformation, and 18 actuator parameters). Facing all of these parameters simultaneously would far exceed the computational capabilities of the largest of the next generation computers. Therefore, a strategy must be developed to break down the design process into a series of layers upon which interactive intervention by the designer through simulation is possible. Computer system designers complain that they have an incomplete strategy for design. Considering the level of architecture, system definition, determinism, and linearity that exists for computers, it is easy to comprehend the difficulty of the task faced by the designer of robots, which is a far less developed technology.

Description: Most industrial robots perform one function, such as pick-and-place, sequential spot welding, or pre-programmed painting. The most advanced system of this type can perform about 20 distinct operations. The concept of multi-task capability means that a wide range of functional tasks can be performed by the same robot. This concept can be illustrated by the example of power steam generator maintenance where the sleeving task may require up to 25 sequential sub-tasks all representing distinct operational requirements. The steam generator presently requires 18 tasks such as plugging and sleeving. The nuclear steam system of PWRs represents 10 distinct system component tasks such as the steam generator, pumps, and valves.

The combined generality of system tasks, component tasks, and sub-tasks is the main reason why a generic technology is needed for a multi-purpose robot to work in an unstructured environment. Should the unstructured nature of the task be articulated by unknown or unfriendly forces, the need for generic technology becomes even more critical.

The reach of the arm directly affects the size of the operational envelope or field of movement of the manipulator arm. Small arms (of 3 ft. reach) usually cannot duplicate the scale of human motions. Many maintenance tasks for nuclear reactors and some military applications require arms six feet long. Unfortunately, the stiffness of these arms is inversely proportional to the cube of their length, i.e., they bend easily. The reach concept of the arm is much more involved than it first appears. To be able

to approach an extreme position and remain dexterous is usually not possible. As one approaches the limits of the operational volume, dexterity deteriorates rapidly. Maintenance tasks such as steam generator sleeving require high dexterity throughout the work volume. The absolute precision of most industrial robots is no better than 0.05 inch and many are far less accurate. Yet many assembly, welding, and light machining operations require a precision of 0.01 inch. Further, fine positioning to 0.001 inch is sometimes necessary. For example, in nuclear reactor maintenance the overall precision must be equivalent to that of a portable machine shop. This level of precision puts an unusually demanding resolution requirement on the actuators and their control system. The control encoders and actuators must be capable of steps of 10 seconds of angular rotation. Most actuators fall far short of this, especially if they must provide a high load capacity.

In addition to these precision requirements, the more difficult condition is to maintain precision while the manipulator experiences large load variations. It is common for external loads to degrade the unloaded precision by a factor of 10. The reader can prove this reality to himself by "shaking hands" with a few industrial robots. It is not uncommon to easily achieve oscillations of 1/4 inch in magnitude. Many operations in space will require high levels of precision (1 to 10 thousands of an inch) even when the robot structure is disturbed by forces generated by the process being performed. The 5,500 lb. Cincinnati Milacron T3-776 industrial robot, for example, deforms 20 times (0.200 inch) its resolution (0.010 inch) under its payload of 150 lb. Space station robots will necessarily weigh 1/20th of this robot's weight to create a force of 75 lb. To achieve the needed level of precision, the robot will have to be made "electronically right," a development objective now under way in some research laboratories.

Cutting, routing, bending, drilling, and force fit assembly induce process disturbances. The availability of these processes would significantly reduce the otherwise large inventory of parts that would be required to repair major space station damage (however infrequent). These processes would further simplify the overall design of the station with the probability of also decreasing its weight. Precision light machining by generic robots would reduce the number of heavy dedicated machines required to perform experiments or manufacturing in the lab modules. Such precision is essential to the handling and repair of precision lab instruments even requiring a level of miniaturization not normally addressed in robot structures.

Certainly, precision robots can also be used to make critical dimensional measurements as a way to prepare for required repair or adjustment. It would be highly desirable if a robot could repair a neighboring robot system. If any of these functions involve the human operator, precision in the slave robot would accelerate his task rate, reduce his fatigue, increase his work time span, and reduce the need for his full concentration during oversight.

A reality of space operations that deserves early attention is the need for near optimal design of a facility for which there will be only one prototype. Hence, CAD must be used in every aspect of the system's design and operation. This is particularly true in robotics, where most industrial systems are designed before CAD tools are employed to their full effect. The result of the CAD effort will be a complete data base about the "as designed" space station which must be updated to account for the "as built" system. Once such a data base exists, it can be used to plan for various tasks either by simulation or by semi-automatic planning using AI principles. The "as built" data base becomes critical when either unproven maintenance activity is being undertaken or when

responding to emergencies. For example, it may be possible to superimpose actual visual feedback with the stored data base scene where differences may be isolated either by computation or by the human operator. The data base may be used to display deformations in the robot structure by color coding its surface to visually inform the operator about the condition of the robot.

One of the major issues for the maintenance of satellites *in situ* is the long time delays for a cycle of communication (up to 0.5 seconds). It is proposed to use a predictive display (a ghosted robot) from the data base to smooth out the visual feedback to the operator. This type of technology is needed to train future astronauts and to develop helmet displays that could be used in extra-vehicular activity (EVA).

Industrial robots today have established a very high operating availability of approximately 98 percent. These units are marketed only after prolonged testing and redesign. Nonetheless, in other unique applications, this extensive history is not available to ensure high reliability. This property is especially important in such operations as nuclear reactor maintenance. Failure would mean difficult retrieval and an extended down time (at great cost) of the power plant. Here, the goal is failure in one of 20 field operations (each lasting two to five days). Failure is also unacceptable where human life is involved as in accident missions, military operations, or ocean floor activity. For an integrated system with all technologies implemented, many field demonstrations will be necessary to perfect the system to make it sufficiently reliable. Predictably, the simpler systems having lower intelligence will be substantially more reliable.

Space robots will work in a hard vacuum and in radiation, they will experience thermal gradients, and may be hit by micro-meteorites. Nonetheless, these robots must be as reliable as possible. Failure might mean the high cost of total replacement or that the robot would have to be repaired by a neighboring robot system. This maintenance objective would best be met by using robots made up of modules that could easily be replaced. Redundancy in some of the hardware components (sensors, encoders, and local microprocessors) would be helpful. Unfortunately, the need to be lightweight and compact makes reliability more difficult to achieve. Self-monitoring software similar to that being used in advanced computers would be highly desirable. In this regard, self-calibration of the robot after maintenance or component replacement would be necessary to maintain the match between the control software and the robot hardware.

A-3.5 Internal Decision Making and Control

Summary: As the mechanical architecture becomes more flexible, layered, and generic, it also becomes far less deterministic. Criteria will have to be developed that will internally govern the system to meet its operational requirements. These criteria will be associated with precision, load capacity, redundancy, obstacle avoidance, and internal force magnification. Thirty distinct criteria can be easily identified today. Hence, these criteria will have to be balanced (fused) in real time (in less than 30 milliseconds). This high level of decision making will be essential in all future robots. The criteria will be based on a full physical plant description (model reference). The implementation of this balanced decision making is the purest form of feedforward control. The level of complexity implied would completely swamp any effort to achieve this level of capability by feedback only. Feedback will be used to sharpen the commands generated as a result of an incomplete system model, by an incomplete sensing system, or by an incorrect

balancing of the criteria.

Most robots are now used for low valued functions, primarily handling tasks that add little direct value to the product. They are feasible in today's technology because the function contains almost no disturbance. Important functions (drilling, routing, grinding, and force fit assembly) add high value to the product, but they do contain force disturbances that reduce the precision of the robot due to large deflections. Until this type of function is treated directly without expensive supporting jigs and fixtures, the level of flexibility in batch mode manufacturing plants cannot be obtained and the level of return on investment necessary to drive the technology forward cannot be achieved. This is why robotics today has lost acceptance in the broader community. The opportunity in airframe manufacture, the military repair depots, and in space operations is enormous. Yet the present research priorities in the U.S. will hardly get us there unless we redirect ourselves to the central problem of disturbance rejection in the unit process.

Description: Intelligent control is the local and global control of the system's operation to meet established performance criteria. Sensors transmit status information and distributed or central processors reduce and interpret the data, then send command signals to the actuators to carry out the desired operation. One objective is to make the manipulator "electronically rigid" to resist all work forces with no deformation. Another objective is to make the arm "electronically massless" to make the system respond quickly to commands. A third objective is to make the system parameters "electronically constant" so that system operation, once perfected, would remain invariant.

Another representative objective of intelligent control is enhanced smoothness of the prescribed motion to reduce shock oscillations in the manipulator. Precision under load, not yet feasible with today's manipulator technology, will require real-time dynamic modeling, and a new type of distributed control. Essentially, the large system motion is too highly coupled and nonlinear to respond to sensory data involving deformations occurring at a much smaller scale. Hence, a new layer of control software and hardware must be developed to treat this small scale function.

Vibration oscillations limit cyclic speeds. Experience with mechanical systems indicates that such oscillations are usually generated from shocks in the command signals. This means that the simple start-stop (bang-bang) control of some systems is the worst possible approach. Generalized motion programming synthesized to enhance the smoothness (shocks occur only at the higher derivatives) is now being developed based on the wide experience derived from the programming of read-only memory (ROM) machines such as automobile cams.

Industrial robots do not exhibit perfectly invariant parameters within the complex control and structural subsystems. The sources of the parametric variations may come from changes in actuator electrical resistance (or hydraulic fluid temperatures), friction in joints, and dimensional changes due to temperature fluctuations.

Implicit parametric variations also may be due to imperfect numerical values used in the deterministic model. The objective would be to characterize these parametric variations and to develop a self-organizing adaptive system to compensate for these variations with reference to the nominal deterministic model. Such a self-calibration system was recently demonstrated to maintain positional accuracy of an assembly robot.

Intelligent control encompasses all deterministic techniques applied to the robot's operational software, which is used to enhance its precision, speed, smoothness, disturbance rejection by modern control methods, digital control, and adaptive control. The control software must be defined in terms of a complete parametric description of the system's link dimensions, deflection rates, mass content, and actuator control parameters. Such a detailed parametric identification can only be achieved by a high level of metrology - a technique now being formulated in research labs. In fact, since some of these parameters will change over the life of the machine, some aspects of this metrology may need to be aboard the space station, especially when modules are either replaced or interchanged.

Intelligent control then depends on a complete and accurate analytical model that must be calculated in real time (less than 30 milliseconds). This model can then be used to train astronauts, to perfect dynamic collision avoidance techniques, docking procedures, and compliance control. Layered control of two or more scales can create a hierarchical architecture for the system hardware and software known as control-in-the-small that is much more effective in providing "feedforward compensation" to reject force disturbances in such tasks as light machining. This sophistication is warranted because of the high level of deformations that result since the robot must be as light as possible. Elimination of these large deflections not only makes precision tasks feasible, it also significantly reduces confusion, fatigue, and frustration as the operator tries to do this type of task manually. Since the system is highly nonlinear and coupled, fixed control laws (now the norm) are incapable of providing optimum response to a wide variety of task requirements, speeds, and disturbance rejection. Hence, adaptive control techniques must now be developed for these complex multi-input multi-output nonlinear and coupled systems that will be heavily influenced by actuator train and link deflections.

This development objective is one of the most complex tasks facing the research community. Presently, laboratory simulations promise to treat 6 DOF in the large plus six or more deflection parameters in the system structure. It is not yet possible to predict the level of computational technology required to perform this adaptive control in real time. It has been shown, however, that the sampling rate of this process directly affects system stability. Beyond this level of understanding, there will be a concern for the level of reaction forces (shock level) transmitted through the base of the robot to the space station structure. These forces could easily disturb the environment of critical laboratory operations. Also, criteria must be established for the balance of 12 actuator forces (and other parameters) to create six desired force components on objects held jointly by two robots (dual robots). This dual robot problem is quickly expanded to one of six parallel acting robots when developing the operational software of a six-legged walking machine (24 or more inputs to create six outputs). Each of the forces at the feet of these legs must be controlled so as not to disturb or deform the space station structure while the robot is walking. This problem represents the most advanced form of intelligent control and will require a major theoretical development.

Internally, robot manipulators that are highly deterministic usually have six inputs to develop six outputs. Should more inputs (say 10) exist, the system becomes redundant (four extra DOF) and uncontrollable by standard techniques now used for industrial robots. The array of 10 inputs must be balanced (in terms of force, speed, energy, and power) to carry out the desired task at the end effector. Hence, AI principles will be necessary to evaluate the task, determine if the robot should be reconfigured (dimensions changed, modules added or removed, and if larger load capacity is required), assess the level of precision required, and use disturbance rejection software if needed. A very

high level of AI must be developed to properly use a generic, modular, precise robot in space operations.

The type of AI that is actually required, however, will depend on technology base issues found in the computer and mechanical engineering fields. The pace of development of computer technology makes the whole concept of the space station feasible. The pressing reality for industrial robots is that computer integration has occurred only to satisfy the most undemanding unit processes (painting, handling, and welding) or applications (low value-added operations in manufacturing). Consequently, a broad-based effort by NASA to integrate computer and control technology with generic mechanical architecture would appear to be essential for space station operations. It would also have potential value in significantly enhancing productivity in manufacturing.

The promise of computer technology for space station automation and robotics is based on the broad spectrum of these technologies from the component level to the system level:

- VHSIC chips
- arithmetics
- array processors
- minicomputers
- supercomputers

This collection suggests that no computational needs in robotics should go unattended since all components in the robot system (sensors, actuators, and structure) can now be brought to a much higher functional level. There should be no reluctance to match the architecture of all components to the wide availability of computer architecture and vice versa.

Much of this need to integrate computer technologies has been described elsewhere in this report. Some of these key areas will be briefly repeated here for completeness.

Because of the requirements for low weight, versatility to respond to unknown tasks, autonomy to carry out continuous inspection, precision in unit processes (such as drilling, routing, and forming), collision avoidance in a complex and changing environment, and access by humans for intervention and supervisory control, the level of computer integration will have to far exceed any previous effort. It will require extraordinary care in structuring the research and development program. In every case, direct support must be maintained in the form of accurate numerical documentation from the data base - a level of information never before attempted for robotics. This means that all activity should be quantified and programmed to minimize the level of uncertainty. Uncertainty in the operation of the robot should be accepted only when the benefits are very high, e.g, for collision avoidance, and high levels of dexterity to carry out complex operations. This level of uncertainty and the associated need to employ principles of AI becomes pervasive in dual arm operations, walking machines, docking operations, automated inspection, and motion planning in cluttered environments.

At the other end of the development program, the need to design the complex hardware and software for this advanced robotics technology must be addressed. Thus far only minimal efforts to develop a technology base for robot system design has been pursued. Essentially, CAD technology must precede the operational technology. With CAD graphics capability, this technology can be used to develop the required training

facilities for astronauts to prepare for space station activity. Because of the need to use a minimum number of distinct components to build up the consort of robot systems to be used in space, hardware modularity will greatly reduce the size of the on-board inventory (a high priority) required to maintain or update this technology. This approach means that the software will also have to be made very modular to match this special architecture. This modular approach will permit the addition of joints, the changing of link dimensions, and the increase or decrease in compliance. The following is a partial list of such modules:

- actuator control
- sensor data reduction
- end effector operation (special tools [drilling and welding])
- docking procedures
- satellite motion identification software
- fault isolation technology
- vision control
- local servo motor control
- force sensors
- micro-manipulator control
- tactile array sensor software

3.6 Mobility and Portability

Summary: For mobile robots, no fixed base can be used as a coordinate reference. This constraint introduces significant navigation and parametric location requirements. Vision controlled automobiles, hovering aircraft, tracked vehicles, walking machines (and combinations of these) can be used for sentry duty, physical security, materials handling, runway repair, and weapons removal and demolition. Research problems include navigation and positional accuracy, stability in rough terrain, and teleoperation from a standoff position.

Description: Mobility implies that the system would be able to traverse an obstacle strewn area. To date, no such system exists in the general sense. Special tracked vehicles, track followers, and wheeled vehicles are available that can move over relatively smooth surfaces (or fixed tracks) with minimum obstacles. Unfortunately, many applications require greater capability in dealing with obstacles. Mobility would have real significance to surveillance and to dedicated autonomous units for military applications, accident missions, and ocean floor activity. During the past 20 years, significant laboratory work has been continuing on the generic concept of walking machines for mobility purposes.

With regard to space station operations, a major issue for the space station is to develop the ability to perform planned or emergency repairs involving assembly and disassembly tasks such as:

- materials transport
- satellite capture
- service orbiting platforms
- inspect station structures
- inspect solar panels
- inspect tension cable telescopes

The question of tethers and on-board power, intelligence, and inventories of replacement parts also must be addressed. There are three mobility approaches for space platform operations: rail transport, crawling, and free flight.

Rail transport requires tracks to be overlaid over the whole platform structure. It carries an increasing weight penalty as the station grows in size. It appears to be difficult because of its limited motion range to avoid all obstacles. Tracks would provide a high level of reliable motion with precision, high load, capacity, and very efficient energy usage.

Crawling technology probably would involve some form of walking machine either tethered or with its own power package. Its relatively low weight would not grow with the size of the station and it would be fairly energy efficient. However, it would move slowly and involve a very high level of machine intelligence, as yet undeveloped, to govern the motion of its legs.

A free flight system would carry its own power package to maneuver by thrusters or by jumping from one part of the station to another. This method is relatively energy intensive, involves time consuming docking and rigidization procedures, is slow, and would have a low load capacity. It would be less reliable than the other approaches and would potentially create problems with its thruster plumes. It is, however, the most near term technology available but would carry a fixed weight penalty when ignoring its fuel consumption. With the full development of the space platform, some balanced combination of all three of these concepts probably will be used.

3.7 End Effectors

Summary: End effectors are the tools attached to the end of the manipulator to do specialized tasks such as welding, drilling, and locking or unlocking bolt assemblies. Frequently, specialized tools must be interchanged, a process that must be time efficient and reliable. It appears that a new generic hand should be developed to reduce the number of specialized tools needed to perform a range of unstructured tasks.

Description: End effectors are the tools attached to the end of the manipulator. They may be either the specialized tools attached to the end plate of the robot (drilling, routing, and welding) or dexterous multi-fingered hands that allow general manipulation of the work in progress. Some end effectors are multi-purpose devices in the same sense that the human hand is able hold a hammer, screwdriver, or other tool. Generally, the complexity of the terminal device is an inverse function of the complexity or dexterity of the arm. As the technology matures, it is expected that general purpose terminal devices (hands) will reduce demands for versatility on the manipulator arm, i.e., small end effector motions (in the form of a three-DOF to six-DOF micromanipulator) will make large system motion less necessary. The normal medium size gripper of today is a simple pair of parallel fingers capable of holding a 5-inch weight of 10 lbs. Generally, these devices are clumsy and require excess maneuverability to grasp a generic object. Frequently, they incorporate some elementary force and proximity sensing. End effectors for drilling, sanding, and painting are being developed. Specialized tools of the type being considered for the space station are also being developed or can be found in other applications such as remote maintenance of nuclear reactors. These tools must be relied on to perform precision operations that must be done during space station assembly or as the result of damage to the station.

A new generic hand is required. This hand should have three or more compliant coordinated fingers of medium dexterity with good incremental force sensitivity capable of grasping and orienting an arbitrary object in space. The power source and intelligence for this generic hand should be contained within the unit itself because of the difficulty of passing control forces through the wrist of the manipulator. Leakage of hydraulic fluids would limit the usefulness of such a hand. Hence, miniaturized prime movers must be developed for this application. The fingers for this generic hand should employ a robust, low hysteresis touch sensor with one gram sensitivity and a dynamic range of 1,000 to one. The desired resolution would approach 1,000 points/in.^{2}. Preferably, the sensor would process this force data locally at the sampling rate of 100 Hz. Once the technology for such a hand has been demonstrated, it will be necessary to fill out the spectrum between it and the specialized devices prevalent today.

Frequently, the handling of small and delicate objects will be necessary to perform laboratory experiments, remote satellite maintenance, or reassemble a satellite. The variety of these smaller objects will require the use of a conforming dexterous end effector, usually conceptualized as a multi-fingered hand. Such a hand will not allow for precision positioning without the human's hand-eye coordination as part of the control loop. The use of dexterous hands will be demanding of the crew's time and should be implemented primarily as a device to treat specialized tasks.

One of the considered needs for space station assembly is a variable compliance capability in the end effector to assist certain forms of slip-fit joining of parts. Generally, high compliance can be used when precision is already built into the parts. The opposite (high stiffness) generally means that precision operations (i.e,, light machining) can be undertaken. Hence, the governing software must be able to adjust the system to be either passively compliant or electronically rigid. The fingers of this dexterous hand may use fiber-optic eyes for inspection purposes and tactile surfaces to help identify objects when either direct or indirect vision is unavailable. Tactile arrays have yet to be used to do more than provide threshold information about an object communicated directly to a computer or to a visual display to the operator.

A-4.0 Human Interface System

Even the simplest robot needs human supervision. The way the robot receives instructions, reports results, or asks for guidance is called the human interface system. Robots today require detailed instructions in rather explicit form, and although they do not yet score well on IQ tests, they do perform complex tasks and adapt to a variety of unplanned environmental conditions in narrow areas of expertise.

Semiautonomous robots require a far more complex human interface than autonomous robots. Man and robot each are part of a symbiotic system in which the human operator provides guidance while the robot does the work. At one extreme of this relationship is the pilot who flies a robot plane based on sensor data fed to a ground or airborne human interface station. Many so-called tele-operated systems are variations on this theme. NASA has one on the space shuttle, and many are used in nuclear reactors, underseas, and elsewhere. At the other end of the spectrum, humans do not control the actuation system, but communicates with the computational (cognitive) side of the robot. Here the person aids in decision making, data interpretation, and in planning or evaluating plans. Thus, the human interface can vary from a simple set of switches, to computer terminals, fancy harnesses, and complex multi-screen graphics systems; and all

depend on the type of interaction needed for the robot and the job to be done.

As robots become more complex with an increasingly self-contained decision making capability, the temptation is to assume that the machine can be considered autonomous. In fact, we believe that while human intervention will be less frequent, when it is required it will occur at a higher level and therefore require a higher quality of interface (visual, kinesthetic, and voice). This interface will be increasingly analog because of the density of information flow that 'ill be required. As system technology develops, there will be a greater need for man-m .chine interface - not less. This boundary should be moved slowly toward less frequent interaction, but it rarely should be eliminated entirely.

The overall question of teleoperation involves the relative need and what type of tasks will be suitable for human intervention (telerobotics), supervisory control (telepresence), or direct human control (teleoperation). On this question intelligent people disagree. Some members of the committee believe that structure can be built into the task that will make human intervention all but unnecessary and therefore the additional investment for human control is not warranted. The case is exemplified by the planned change out of ORU modules. Others believe that there are unexpected events that cannot be predicted, are impossible to plan for, and which are potentially so damaging (note that 40 percent of the down time of nuclear reactors - one day in three - is unexpected) as to make human judgment and kinesthetic commands essential. The debris in space can cause this level of uncertainty because of significant damage that even small flecks of paint can cause.

It is clear that every step must be taken to structure operations in space whenever possible to permit autonomous functions (with its associated lower cost and high payoff). The reality of unplanned for and unexpected, unstructured tasks - which might result from an accident, debris damage, or human error - is that human judgment and intervention will be necessary, and must be available for quick implementation. This class of unstructured task must be carefully evaluated to obtain actual operating requirements. Until this is done, the relative need for telerobotics in support of autonomous operations will not become clear. It is suggested that there is no "tech base" conflict in these possibilities.

A-4.1 Operating Requirements

Summary: Much of the development work now done in the U.S. concerns autonomous machines. For repetitive and highly structured manufacturing tasks (pick-and-place, spot welding, and spray painting), AI can be transformed into an operational machine intelligence capable of duplicating or surpassing human judgment and decision making capability. But robots probably will not have the required level of intelligence for complex assemblies, nuclear reactor maintenance, or avoidance of intelligent enemy maneuvers for at least 20 years. The best near term alternative is to balance human and machine capabilities. As technology improves, machines will gradually replace men.

Description: The less structured the task, the more human interaction that is needed. An unstructured task is one in which the operational environment is not quantitatively known to the operator, the machine intelligence, or the data base. Nuclear reactors, for example, are documented as designed, not "as built," and often they are provided no reference benchmarks. Unstructured tasks require human directions. These in turn

require sensory perception. Machine intelligence enhances this perception and makes system performance more accurate and rapid. Most systems for remote operations provide a modest capability to treat the lack of definition represented by the unstructured task.

In space, the number of distinct tasks a given robot system can perform is a dominant consideration to reduce the number of such systems necessary to operate in space. Fewer robots mean reduced weight and a smaller replacement parts inventory. Some of the unit processes that must be performed are:

- Operate simple mechanisms, latches, cranks, slides, and handles.
- Join and fasten, force fit connectors, spot weld, form, bolt, screw, lock, coil, rivet, and electron beam weld.
- Precision machine, grind, sand, brush, drill, rout, trim, and cut.
- Transfer parts, handle limp and slippery materials, and warehouse.
- Inspect seams, surface flaws, and meteorite damage on solar arrays, thermal radiators, windows, and mirrors.

In addition, several complex dynamic motion tasks are either necessary or may be tested for space station operation:

- Docking and grappling maneuvers.
- Reactionless operations.
- Stabilization by appendage motion.
- Rigidization.
- Catching and storing space debris.
- Throwing and jumping.
- Dual robot operations.

Robot systems are intended to carry out some in-depth functions over the long term, such as:

- Clean room operations in both manufacturing and experimental lab modules.
- Self-measurement of space station dimensions over large distances.
- Space station assembly.
- Repair and maintenance throughout the space platform.
- Repair and maintenance of satellites in orbit.

This formidable spectrum of physical tasks strongly argues against using many specialized dedicated machines in favor of generic multi-purpose robots with an ever increasing level of flexibility. This need for generic technology may be instrumental in leading the U.S. away from numerous highly dedicated machines now in use. Because space operations are expensive and time may be of the essence in emergencies, the time-efficient operation of the supporting robot technology is an important criterion for its design and implementation. The reference would either be the time for the human alone to do similar functions on earth or the astronaut in EVA. The need for productivity is highlighted by the fact that the space shuttles have experienced four to six failures per day and that docking with a satellite may require eight to 10 hours.

While most operations in space are not repetitive, they are structured and subject to simulation and planning on the ground. Accurate situation assessments can be carried out numerically without human intervention. The data base and imbedded AI technology

can be used to eliminate time consuming trial and error motion trajectory selection in an obstacle strewn environment. Once a complex motion has been selected, it can be programmed by human control on the ground and repeated automatically by machine intelligence. In this regard, the CAD data base can have a high payoff as a basis for astronaut training. In the robot structure itself, high load capacity, precision resolution, combined with low stiction and backlash can significantly reduce human fatigue and frustration. The history of complex technologies such as nuclear reactors shows that they are down for repair about 33 percent of the time with 40 percent of this downtime due to forced outages. Space systems will probably have such problems principally because of their complexity and because initially they will be prototype systems.

This suggests that space operations and maintenance will require human judgment based on uncertain information. In fact, even though there is a pressing need for autonomous operation to reduce the burden upon the on-board personnel, as the technology becomes more adaptive and more capable of doing complex operations, human intervention becomes more important, not less.

Human intervention is best provided in terms of kinesthetic interface because of the high rates of analog information transfer in the manual controller. Because the operator will have to control a large range of unique robots (many that will be reconfigured to meet a given task), the controller must be universal with software capable of driving any robot. This universal nature also reduces the training effort faced by the operator. The "universal" requirement means that the coupling software must operate in real time and be highly adaptable. It must enhance signals to the operator, filter out jitters or gross errors from the operator, and perfect global commands, such as constraining the end effector to track the surface of a sphere, mathematically change orientation, change scales, or monitor manipulator operations for accidents, impending collisions, and overloads. When one operator must simultaneously control both arms in a dual arm system, then the quality of the interface becomes critical.

An advanced manual controller would be invaluable as a training aid. The "universal" aspect of the manual controller also has a significant impact on the design of the man-machine interface. It means that the master (or manual controller) can be optimized for its primary interface with the human operator, it can be made lightweight, and it can be kinesthetically transparent. The slave (the robot manipulator) can then be optimized for its principal range of functions without being compromised by constraints or limitations that would occur from a geometrically similar master-slave combination. Dissimilar geometries means that the software will have to be far more general but will provide a total system that is much more adaptable to changing applications.

A-4.2 Tele-operation

Summary: The reality of unstructured tasks, which might result from an accident, debris damage, or human error is that they will require human judgment. These tasks must be carefully evaluated to obtain actual operating requirements. Until this in-depth assessment of the task requirements is pursued, the actual need for tele-operation will remain poorly defined.

Description: Tele-operation often has been interpreted as an archaic class communication link between similar master and slave robot subsystems. The Air Force has recommended development of a concept of telepresence that is a high quality enhanced interface.

Telepresence suggests, however, a full commitment by the operator in the performance of the tasks. In some specialized, unstructured, or emergency tasks this may be the best use of resources. For tasks that can be structured (and they should be if at all possible), this level of operator commitment would not be economical.

To attain this goal of supervised autonomy, where humans plan operations and then intervene only when necessary during execution, a level of internal decision making must be achieved. If this level is attained, the data and criteria prioritization would be the same either to support computer or human decision making. Supervised autonomy is the current balance of human-machine interaction and does not lead to any direct contradictions in the required technology. In the factory or repair depot, many practitioners in robotic implementation have discovered communication mismatches between system components, primarily at the machine level. Very highly integrated communications will become imperative as the data base of the factory of the future becomes more easily addressed. Since no one manufacturer will supply all factory units, standardized interfaces will become very desirable. At the other end of the spectrum are the interface needs between robot components such as sensors, actuators, and distributed processors. Some of the issues are voltage levels, rates of sampling, numbers of channels, multiplexing, analog to digital-digital to analog (AD-DA) converter technology, scaling, synchronization, error filtering, noise reduction and isolation, and data compaction.

Obviously, both hardware and software issues are involved. The goal must be to standardize as many of these interfaces as possible. The National Institute of Standards and Technology robotics program is pursuing this objective as one of its major missions. The Navy is working on ways to establish accurate long range communication with untethered vehicles in the difficult medium represented by sea water that contains debris. In the Oak Ridge National Laboratory fuel reprocessing plant development, tethers would drastically limit mobility of the maintenance and handling equipment. Therefore, special frequency radio wave systems are planned to ensure complete mobility. Space may be thought of as having the same array of interfaces as would be found in a modern factory. The highly desirable feature recommended for space station systems is modularity to enhance maintenance and technological updates. The more modular the space station and its supporting systems (robots), the more concern there must be for interface issues. The most dominant interface is between man and machine but others exist:

- Laboratory subsystems.
- Astronaut support.
- Satellite control and maintenance.
- Sensing and inspection.
- CAD data base.
- Hierarchical decision layering.

Unfortunately, some communications will be delayed between the space station and earth, with satellites, or with RPVs working on satellites. Finite time windows will be available (measured in hours) such that time may be of the essence. Very early in the program, the Air Force should try to establish standards for interfaces between its principal sub-modules at all levels, from specialized tools to space station communications. The NIST factory floor interface program may be a real asset in this effort. The full array of housekeeping chores, inspection, maintenance, and response to emergencies will overlook the limited number of personnel in space. Every effort must be made to automate as many of these operations as possible. This objective can be met only by employing a high level of machine intelligence frequently based on principles of AI.

Because a continually updated data base will be used for space, the work environment will be reasonably well structured. This means that semi-automatic inspection, near optimal trajectory planning, situation assessments, and collision avoidance are feasible for space operations. The commands from the human operator through the manual controller can be perfected in terms of functional requirements stored in the data base. Jitters and gross errors can be mathematically filtered, motions once taught can be repeated without operator involvement, and a ghosted robot can be used to guide the operator in planning motions in an obstacle environment.

Since humans cannot make unaided precision measurements or perform precision operations especially under disturbance, machine intelligence can be used to augment the operator's skill. This becomes especially necessary in the operation of dual arm systems and the automatic foothold selection and walking operation of multi-legged structures. Machine intelligence will be used to provide more precision or dexterity, to search for system faults, and to call for and plan corrective action. This level of machine intelligence far exceeds that available today in industrial robots. It will be achieved only with a consistent and long term commitment to a broad-based program.

A-4.3 Universal Manual Controller

Past master-slave systems used manual controllers that were geometrically similar to the slave (or driven) manipulator. This meant that a compromise between the two was the result. Today it is feasible to develop a manual controller that is completely different from the slave in size, geometry, number of DOF, and control parameters. This means the slave can be better optimized to meet its functional needs while the controller can be better designed to interface with the human. On this basis, the controller becomes universal, i.e., it is able to drive any slave system.

Some of the desired attributes of the manual controller are:

1. lightweight
2. compact
3. stowable
4. portable
5. adaptable
6. minimum friction (stiction)
7. minimum mass
8. small minimum step (resolution)
9. transparency of force feedback signal

A-4.4 Operational Controller Software

Summary: To make a controller universal requires that real time software be developed to transform signals from the controller into meaningful command signals to the slave robot. If more than one distinct slave is possible (say there are several stand-off manipulators) as would occur in space, then each combination would require its own on-board communications software. This software must operate in real time (under 10 milliseconds).

Description: The controller software must transform all encoder, force, and current signals into generic digital information about the state of the slave, the controller, or the interactive wishes of the operator. It must develop command signals to the active elements of both controller and the slave. Since extra DOF may occur in both systems, criteria-based decision making also will be essential. Clearly, the duality of these transformations, the opportunity for human intervention at all levels, and the mass of the information flow creates a complexity exceeding that of just controlling the slave robot alone. Transformation duality makes possible changes in scale, filtering of gross errors or jitters, reorientation, referencing, and force smoothing. Should time lags of 0.5 to 2.0 seconds exist, it appears possible to use smoothing, projected signals, and visual ghosting to make the duality still work. Essentially, the system is two robots communicating with each other in real time.

Initial prototype software packages do exist in a few research laboratories. A major effort would be required to develop a portable and reliable software system such that one controller could drive any number (say 10) of distinctly different slaves.

APPENDIX B: SCHEDULE OF COMMITTEE MEETINGS

First Meeting
Aeronautical Systems Division
Wright-Patterson AFB, Ohio
26-27 February 1987

Agenda

Thursday, 26 February 1987

0800	AFSB Convenes	
0815	Welcome to ASD	Col. Walton
0825	Introduction and Chairman's Overview of Study	Dr. Gerhardt
0840	Administrative Announcements and NRC Bias Statement	Vernon H. Miles
0855	Automated Airframe Assembly Program	Mr. Rasmusen (MLTM)
0925	Discussion	AFSB
0940	Robotics Centers of Excellence	Mr. Lagnese (MLTC)
1000	Discussion	AFSB
1015	Break	
1030	Intelligent Task Automation	Mr. Griswold (MLTC)
1050	Discussion	AFSB
1100	Flexible Assembly Subsystems	Mr. Brandewie (MLTC)
1120	Discussion	AFSB
1130	Robotic Telepresence	Capt. Julian (AAMRL)
1210	Discussion	AFSB
1230	Lunch - Executive Dining Room	
1330	Robotic Refueling & Munitions Handling	Capt. Davis (FIER)
1410	Discussion	AFSB

1430	Pilots Associate	Capt. Gunsch (AAA)
1510	Discussion	AFSB
1530	Break	
1545	Robotic Air Vehicles	Mr. Blair (AAA)
1625	Discussion	AFSB
1645	Adjourn Meeting/Return to quarters	
1830	Reception at Officers Club	
1930	Dinner	
2100	Return to Quarters	

Friday, 27 February 1987

0800	AFSB Reconvenes	
0810	Artificial Intelligence Institute Overview of AI	Vince Russo Maj. Steve Cross (AAX)
0850	Discussion	AFSB
0910	Break	
0925	AFSB Executive Session Discussion of: Scope of Study Schedule Organization	
1200	Lunch - Executive Dining Room	
1300	AFSB Reconvenes Executive Session	
1500	Adjourn	

Second Meeting
2100 Pennsylvania Avenue, NW
Room JH 455
Washington, D.C.
9-10 April 1987

Agenda

Thursday, 9 April 1987

0930	Introductory Comments Goals of meeting Agenda	Les Gerhardt, Chairman
0945	Air Force Organization	Howard Leaf
1015	Break	
1030	NASA Robotics Program	Lee Holcomb
1130	DARPA Robotics Program	Bob Rosenfeld
1200	Working Lunch	
1300	Navy Robotics Programs	Bill Butler
1400	National Bureau of Standards	Sandor Szabo
1500	Break	
1515	Automated Testing	Tony Coppola, RADC
1615	Discussion Period	
1715	Return to quarters	
1830	Social Period	Committee Room 1, 2nd floor Joseph Henry Bldg
1915	Dinner	Committee Room 1,, 2nd floor Joseph Henry Bldg

Friday, 10 April 1987

0830	Committee Discussion Identify Issues Identify Needed Information Report Outline	

1000	Army Robotics Programs	Chuck Shumaker, Army HRL
1100	Continue Committee Discussion	
1200	Working Lunch	
1500	Adjourn	

Third Meeting
McClellan AFB
Mather AFB
Travis AFB
California
17-19 June 1987

Agenda

Wednesday, 17 June 1987

0845	Welcome to McClellan	Maj.Gen. Greer
0900	Introductions/Overview of Meeting	Chairman Gerhardt
0910	Administrative Announcements	Vernon H. Miles
0915	McClellan AFB Mission Overview	
0930	AFLC Organization & Robotics Needs Joint Logistics Commanders	Ben Williams
1015	Packaging & Distribution	Col. Miller & Ms. Andrews
1045	Break	
1100	Tour of Packaging & Distribution Facilities	Col. Miller & Ms. Andrews
	Tour of Reclamation Facility	Col. Miller & Ms. Andrews
1230	Lunch	
1330	Tour of Hydraulics Facility	Col. Murphy & Mr. Orr
1400	Tour of Plating, Bonded, NDE & Masking Facilities	Col. Murphy & Mr. Orr
1500	Tour F-111 PDM Line	Col. Murphy & Mr. Orr
1530	Tour of Van Shop	Col. Murphy & Mr. Orr

1630	Return to Quarters	
1800	Social Hour	
1900	Dinner	
	Thursday, 18 June 1987	
0800	Discussion Period	Chairman Gerhardt
0900	Break	
0915	Executive Session	Chairman Gerhardt
1100	Depart for Mather AFB	
1200	Lunch	Mather Officers Club
1330	Presentations/Tour	320th BMW
1430	Weapons Loading Demonstration	320th BMW
1630	Discussion	
1700	Depart for Travis AFB	
1830	Social Period	Travis Officers Club
1930	Dinner	Travis Officers Club
	Friday, 19 June 1987	
0800	Presentations/Tour 60th MAW	
1200	Lunch	
1300	Executive Session	
1500	Adjourn/Depart for San Francisco Airport	

Fourth Meeting
Hill Air Force Base, Utah
14-15 September 1987

Agenda

Monday, 14 September 1987

0730	Depart Hotel	
0800	Welcome to Ogden ALC and Hill AFB	General Robert P. McCoy, Commander, Ogden ALC
0900	Circuit Card Manufacture Tour	
0930	Optics Laboratory Tour	
1010	Industrial Products Division Landing Gear Tour	
1200	Lunch	Officers' Club
1300	388th TFW Mission Briefing	Col. Boese, Cmdr, 388th TFW
1335	Weapons Load Demonstration	
1410	Hot Pit Refueling Demonstration	
1430	Robotics Discussion	
1500	Potential Applications of Robotics Technology to Tactical Operations	
1600	Air Base Survivability/ Salty Demo Exercise/ CB Decon	
1730	Depart for O'Club	
1800	Social Hour	
1900	Dinner	
2100	Return to Hotel	

Tuesday, 15 September 1987

0730	Depart Hotel	
0800	Explosive Ordnance Disposal	Don Nelson, Naval Explosive Ordnance Disposal Technology Center, Indian Head, MD
0900	Wheel Deburring and C-5A Brake Assembly C-5A Brake Assembly	Steve Nelson, Chief of Technology and Productivity Section, Director of Maintenance, Ogden ALC
	Laser Applications in AF Depots	
1000	Executive Session	
1130	Adjourn	

Fifth Meeting
National Research Council
2001 Wisconsin Avenue
Green Building, Room 124
Washington, D.C.
5-6 November 1987

Agenda

Thursday, 5 November 1987

1000	Opening Remarks	Chairman Gerhardt
1010	Administrative Announcements	Vernon H. Miles
1015	Space Applications of Robotics	TBD
1115	Robotics for Air Base Security	William J. Witter, HQ DNA/NSNS
1215	Working Lunch	
1300	Review/Rewrite Draft Report	Chairman Gerhardt
1700	Return to Quarters	
1830	Dinner	

Friday, 6 November 1987

0800	Continue Report Preparation
1200	Working Lunch
1500	Adjourn

Sixth Meeting
National Research Council
2001 Wisconsin Avenue
Green Building, Room 124
Washington, D.C.
28-29 December 1987

Agenda

Monday, 28 December 1987

1000	Work Session
1700	Adjourn
1800	Dinner

Tuesday, 29 December 1987

0830	Work Session
1500	Adjourn

Seventh Meeting
National Research Council
2001 Wisconsin Avenue
Green Building, Room 124
28-29 April 1988

Agenda

Thursday, 28 April 1988

1000	Work Session
1700	Adjourn
1800	Dinner

Friday, 29 April 1988

0830 Work Session

1500 Adjourn

Eighth Meeting
National Research Council
2001 Wisconsin Avenue
Green Building, Room 127
29 November 1988

Agenda

Tuesday, 29 November 1988

1000 Work Session/Review of Final Report

1700 Adjourn